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Biomechanical Measures of Lower Limb Variability, and Prediction of Non-Contact Knee Injuries Risk Factors in Male Athletes

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CONTENTS 6

Contents

Tables

Figures

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Msaad Alzhrani

Abstract

Introduction:

Football is one of the most popular sports played globally. Male players constitute 82% of football players around the world. As the number of football players increases, we expect more sports injuries to occur. Knee ligament injuries, such as Anterior Cruciate Ligament (ACL), are considered one of the most devastating injuries because of the consequences from the resulting damage. A large proportion of these injuries result from a non-contact mechanism. Some of the biomechanical risk factors in non-contact injuries are considered modifiable, therefore it is important to understand the mechanism of injury to modify it to be able to reduce or prevent the injuries. Also, recent studies have suggested that movement variability should be considered a potential source of information for analysis in monitoring athletes' biomechanical performance. The aims of this thesis are to assess the performance and performance-variability of frontal plane projection angle (FPPA) and hip adduction angle difference between legs and over season, and its relationship with injury.

Methodology:

After assessing the validity and reliability of FPPA and hip adduction angle during single leg squat (SLS) and single leg landing (SLL) tasks, in a separate study with 15 healthy subjects, using the 2D technique, both tasks were found to be adequately valid and reliable in examining the lower limb kinematics. The main study then was done on 90 male professional footballers with the average age of 18.8±4 years, height 179.2±6 cm, and weight 73.3±6 kg, using SLS and SLL tasks to assess the performance and performance-variability of FPPA and hip adduction angle. The difference of performance and performance-variability of individual lower-limb kinematics (FPPA and hip angle) between legs and throughout the sports season (one year) were examined. Non-contact knee ligament injuries were also recorded. Then, the relationship between lower-limb kinematics (FPPA and hip angle) and injuries were investigated prospectively.

Results:

The performance of the dominant leg was found to be significantly more valgus (greater FPPA) than the non-dominant leg for both tasks in all screening sessions (-1.69° to -5.02° vs. 2.54° to -2.30°), but there was no difference in the hip adduction angle between legs (SLS, 73.15° to 73.47° vs. 74.53° to 75.85°; SLL, 80.91° to 83.55° vs. 81.58° to 85.39°). The overall performance of SLL FPPA ($p = 0.01$–0.0005) and hip angle ($p = 0.0005$) changed significantly over the collection time points. The difference in performance-variability

between legs was not statistically significant for either FPPA or hip adduction angle in all of the screening sessions ($p = 0.08–0.89$), except for FPPA in the start-of-season screening. The performance-variability in FPPA and hip adducting angle were consistent over time (throughout the season) in both SLS and SLL ($p = 0.13–0.61$). Seven non-contact knee ligament injuries out of 75 total lower-limb injuries were reported. Therefore, a prediction analysis was not reported due to the limited obtained injuries. A descriptive analysis was carried out alternatively where injured legs performance and performance-variability showed similar actual scores in both tasks. However, after injury, a statistical test showed that the injured group's performance of SLS and SLL did not change ($p = 0.38–1$), whereas the uninjured group's performance of SLL did change significantly ($p = 0.0005$). The performance-variability of SLS and SLL did not change for both groups ($p = 0.27–1$), injured and uninjured.

Conclusion:

The difference of FPPA performance between legs in both tasks suggests that both legs need to be examined independently when assessing the lower-limb kinematics, rather than one leg alone or using bilateral tasks. Also, the change in FPPA and hip adduction angle over the sports season during SLL suggests that examining the lower-limb kinematics should be done regularly throughout the sport season due to the change of performance, rather than at one occasion. Also, it suggests that the SLL task is more sensitive than that of the SLS in detecting performance change. With regard to the performance-variability, it is unlikely to have a significant impact on overall performance. Finally, in light with predicting the non-contact knee ligament injuries using the 2D technique, larger number of injuries is needed to study this point.

Chapter (1)

Introduction

Chapter 1: Introduction

1.1 Knee Injuries in Sport

Sporting activities are increasing every year, involving millions of participants, unfortunately this has meant an increase in the number of sporting injuries (Imamura et al., 2012). Knee injuries are considered one of the most common athletic injuries (Louw, Manilall, & Grimmer, 2008). In the literature, there are two common types of definition of injury, based on the time loss and the need for medical attention (Waldén, 2007). The Council of Europe has defined injury as 'any injury occurring as a result of sports activity and causing one or more of the following: the subject had to stop sports activity and/or could not fully participate in the next planned sports activity and/or could not go to work the next day and/or needed medical attention.' Thus, it is essential to specify the injury definition clearly in every study and to use the most common definition to be as consistent as possible in the interest of improved research quality and benefits. Athletes' injuries, which occur without physical contact, are referred to as non-contact injuries (Yu & Garrett, 2007).

1.2 Prevalence & incidence of knee injuries

Regardless of the definition of injury, more than 8.6 million sports and recreation-related injury episodes were reported every year in the United States (Sheu, Chen, & Hedegaard, 2016). In England and Wales, Nicholl, Coleman, and Williams (1995) reported that every year there are 9.8 million new exercise-related injuries that result in treatment or prevent a person from carrying out their usual activities.

Lower limb injuries are found to be 50–75% of sports injuries among different sports and playing levels (Hootman, Dick, & Agel, 2007; Powell & Barber-Foss, 2000; Rauh, Macera, Ji, & Wiksten, 2007). Louw et al. (2008) found that knee injuries represent about 10–25% of sports injuries in active adolescents. Specifically, injuries to knee ligaments are very common.

Gianotti, Marshall, Hume, and Bunt (2009) reported that the incidence rate of knee ligaments per 100,000 person-years was 1,147.1 for non-surgical ligaments injuries, 36.9 for anterior cruciate ligaments surgeries and 9.1 for other surgeries in the general population in New Zealand. In particular, the most significant amount of time loss in sport occurs in anterior cruciate ligament (ACL) and patellofemoral joint (PFJ) injuries (Starkey, 2000).

The incidence rate of ACL injuries is low, at 0.1–0.3 per 1,000 athlete exposures, according to many published studies that show some difference in rate between the level and type of sports played (Gianotti et al., 2009; Gwinn, Wilckens, McDevitt, Ross, & Kao, 2000; Quisquater et al., 2013). But the impact and burden of ACL injury is high with prolonged rehabilitation and often surgery being required. Patellofemoral pain syndrome (PFPS) incidence rate is about 1.09 injuries per 1,000 athlete exposures, which is greater than the incidence rate of ACL injuries (Myer et al., 2010).

1.3 Method to identify high-risk athletes

The majority of studies use two-dimension (2D) and three-dimension (3D) motion analysis to examine the lower limb biomechanics and its relationship to injuries (Blackburn & Padua, 2008; Ford, Myer, & Hewett, 2003; Hewett et al., 2005; Willson, Binder-Macleod, & Davis, 2008). Each tool has advantages and disadvantages. The 3D system has become known as the gold standard for identifying athletes at higher risk of injury ((Munro, Herrington, & Carolan, 2012).

Examining the lower limb biomechanics during athletic tasks is important as it could lead to strategies to modify the high-risk movement pattern identified. Most studies use 3D motion analysis to assess the lower limb biomechanics (Blackburn & Padua, 2008; Ford et al., 2003; Hewett et al., 2005). However, 2D video has also been used for identifying people at higher risk of knee injuries in a growing number of studies. The frontal plane projection angle (FPPA) has generally been used in these studies for this purpose (McLean, Walker, et al., 2005; Mizner, Chmielewski, Toepke, & Tofte, 2012; Willson & Davis, 2008).

For the screening tasks, the drop jump landing (DJ) task has been used widely to assess athletes to identify those who are at higher risk of ACL and PFP injuries, those at greater risk would appear to have higher knee valgus motion and moments (Hewett et al., 2005; Myer et al., 2010). However, the nature of this task makes it difficult to distinguish between the two limbs as it is a bilateral task whereas most injuries happen during single limb activities (Faude, Junge, Kindermann, & Dvorak, 2005). Single leg landing (SLL) may be relevant for assessment as a unilateral task. Studies have shown that hip adduction and knee valgus is greater when the individual undertakes unilateral tasks than during bilateral tasks (Myklebust, Maehlum, Holm, & Bahr, 1998; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007). According to Munro (2013), individuals demonstrating dynamic knee valgus might be more readily identified by the single leg landing (SLL) screening task than by the DJ task because the SLL creates a greater requirement for the braking of landing forces. However, this has not been studied.

Willson & Davis (2008b) reported the use of the single leg squat (SLS) task to examine the correlation between 2D FPPA and 3D lower extremity inclinations. According to (Whatman, Hing, & Hume, 2011), the SLS can predict the forms of motion expressed while running and can discriminate between individuals with PFPS and those without. Hence, this could be a useful technique for recognising individuals at risk of developing PFPS. Moreover, Munro (2013) asserts that individuals who display enhanced dynamic valgus when performing the SLS will probably display comparable dynamic valgus when performing complicated actions like cutting and landing.

Therefore, using SLS and SLL would appear to be the most appropriate to predict those athletes who are at higher risk of lower limb injuries, because of the advantages and disadvantages of the available tasks.

1.4 2D motion analysis: reliability and validity

The validity of 2D FPPA has been investigated and found to be moderate across some common athletic tasks such as SLS (Willson & Davis, 2008) and drop jump tasks (Hewett et al., 2005; Myer et al., 2010), SLL (Sorenson, Kernozek, Willson, Ragan, & Hove, 2015). But, the reliability of the 2D FPPA has not been studied adequately. Willson and Davis (2008) reported the interclass correlation coefficient (ICC) value of 0.88 for within-day reliability only, whereas Munro, Herrington, and Carolan (2012) reported the within-day and between-day in SLS, SLL and DJ but not the inter-rater and intra-rater reliability. Therefore, new studies should assess the 2D inter-rater, intra-rater reliability, standard error of measurement and small detectable difference.

The main study will assess the individual kinematics measures through an entire sports season, and the relationship between lower limbs kinematics and knee ligaments injuries. It is critical first to investigate the validity and reliability of the method and tools. Study one

(A) examined the validity of the 2D technique compared with the 3D system; study one (B) investigated the reliability of the method within and between sessions. Also, intra- and inter-reliabilities, standard error of measurement and small detectable difference have been established.

1.5 Movements variability

The variability in movements can be affected by many factors such as age, temperature, stage of season, muscle strength and flexibility, surface of play and athletic shoes. In this chapter, we will investigate each of these factors, and how it might affect the individual variability during the sports season. For simplification, we have divided these factors into three main categories: variability over time (age, temperature and stage of season), variability due to performance (muscle strength and flexibility; and warm up), and variability due to friction (play surface and athletic shoes). No previous studies have investigated the kinematic movement variability of athletes across an entire sports season, which is one of the objectives of this thesis.

1.6 Predicting athletes at high risk of knee injuries

Examining the lower limb biomechanics during athletic tasks is important in order to direct interventions to modify high-risk movement patterns if they are present. Most studies have used 3D motion analysis to assess the lower limb biomechanics (Blackburn & Padua, 2008; Ford et al., 2003; Hewett et al., 2005). 3D motion analysis helps the examiner to look at all three planes of joint motion and has been considered to be the gold standard.

However, 2D is the other method that has been studied as a tool to identify people at higher risk of knee injuries. The frontal plane projection angle (FPPA) has been used for this purpose (McLean, Walker, et al., 2005; Mizner et al., 2012; Willson & Davis, 2008). The validity of the FPPA method used with 3D has been investigated during some athletic tasks (McLean, Walker, et al., 2005; Willson & Davis, 2008).

The 3D system has some disadvantages such as the cost of the system, the cost of use, the length of time needed for data collection and analysis, the need for a trained individual to use the system and the inability to use it outdoors or transfer it to data collection sites. These disadvantages have created a gap between research and clinical practice because assessing the players usually happens in the sports clubs and clinics where a simpler and easier tool such as the 2D system is required to predict players who are at higher risk of injury and to make the decision of player return to play. Therefore, studying the 2D tool is very important so it can be used in clinics and sports clubs regularly. However, no prospective studies have examined the relationship between the 2D and lower limb injuries, which is one of the objectives of this thesis.

1.7 PhD Objectives

1. Review the literature of lower limb sport injuries mechanism and risk factors.
2. Review the literature of lower limb screening tools, which can identify the risk factors of injuries.
3. Assessing the reliability and validity of 2D video to assess SLS and SLL performance.
4. Assessing the SLS and SLL performance between legs and across season.
5. Assessing the performance-variability of individual lower limbs kinematics between legs and across season.
6. Examining the relationship between kinematic measures of lower limb joints and knee injury prevalence in male footballers, prospectively.

Chapter (2)

Literature Review

Chapter 2: Literature review

2.1 Introduction

All physical activities are associated with an inherent risk of injury (Waldén, 2007). Sports activities are increasing every year with thousands of participants. As the number of participants increases, we expect more sports injuries to occur in all different types of sports (Imamura et al., 2012). The study of these injuries is important because of the high impact on health and the economy (Waldén, 2007).

Many studies have been conducted to investigate the prevalence and the incidence of sport-related injuries. Regardless of the definition of injury, more than 8.6 million sports and recreation-related injury episodes were reported every year in the United States (Sheu et al., 2016). In England and Wales, Nicholl et al. (1995) reported that 9.8 million new exercise-related injuries result in treatment or prevent someone from carrying out their usual activities occur every year. Marwan et al. (2012) found that 73.8% of 5 sport clubs players have sustained injuries during the last 12 months. It is consequently very important to study how these injuries occurred to find solutions to decrease or prevent the occurrence of injury.

Knee injuries are considered one of the most common athletic injuries. Louw et al. (2008) conducted a systematic review, which reported that the prevalence of knee injuries was 10-25% of all sports injuries in active adolescents. Woo, Abramowitch, Kilger, and Liang (2006) reported that 90% of knee ligament injuries involve the anterior cruciate ligament (ACL) and the medial collateral ligament (MCL). ACL is considered to be one of the most devastating injuries because of its consequences. The complexity of knee structures and the multidirectional forces that affect the knee explain why knee injuries are more severe than injuries in other joints. This complexity makes knee injuries one of the greater time-loss injuries because of the need for surgery or extensive physical rehabilitation before returning to the previous level of activity (Louw et al., 2008).

Therefore, understanding knee injuries risk factors is essential to decrease the high percentage of such injuries among sports players.

2.2 Role of Movements in injuries

2.2.1 What is a sports injury?

In the literature, there is a wide range of definitions of injury (Waldén, 2007). One study defined injury as any condition that caused a player to be removed from a game, miss a game, or to be sufficiently disabled to go to the medical tent (Kibler, 1993). Another study defined injury as an injury received during training or competition that prevented the player from participating in regular training or competition for more than 48 hours, excluding the day of the injury (Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). Some studies considered injuries during competition only; other studies considered both competition and training injuries (Wong & Hong, 2005). Some articles grouped injuries into subcategories with different classifications (Wong & Hong, 2005).

The football consensus group recently recommended that a recordable health-related incident (injury) in athletics is defined as ‘Any physical or psychological complaint or manifestation experienced by an athlete, irrespective of the need for medical attention or time loss from athletics activities’ (Fuller et al., 2006; Fuller et al., 2007). Also, the term ‘incident’ was adopted in this statement, rather than ‘injury’ or ‘medical condition’, to emphasise the desire also to collect syndromic (pre-diagnostic) data and overuse injuries (Timpka et al., 2014). In surveillance studies, the football consensus group recommends including incidents that result from athletics competition and training (Timpka et al., 2014). Furthermore, the Council of Europe has defined injury as ‘any injury occurring as a result of sports activity and causing one or more of the following: the subject had to stop sports activity and/or could not fully participate in the next planned sports activity and/or could not go to work the next day and/or needed medical attention’. Thus, it is essential to specify the injury definition clearly in every study and to use the most common definition to be as consistent as possible in the interests of better research quality and benefits.

2.2.1.1 Prevalence & Incidence

Regardless of the injury definition, 3.7 million sports injuries from people of all ages have been reported annually by emergency departments in US hospitals (Burt & Overpeck, 2001). In England and Wales, Nicholl et al. (1995) reported that 9.8 million new exercise-related injuries result in treatment or prevent someone from carrying out their usual activities every year. Marwan et al. (2012) found that 73.8% of the participating club players had sustained injuries during the last 12 months. Also, 27.7% of all injury-related hospitalisations were as a result of sporting and recreational activities (Burt & Overpeck, 2001).

Conn, Annest, and Gilchrist (2003) found that sports-related injuries incidence rate was higher among the age group of 5- to 14-year-olds (59.3 per 1000) comparing to the age group of 15- to 24-year-olds (56.4 per 1000). It is difficult to compare the incidence rate among different types of sports because each sport has used a different rate calculation. Also, there are different types of incidence rates in the same type of sport based on a number of injuries per hours/activity or hours of athlete-exposures (Wong & Hong, 2005).

The incidence rate is more important than prevalence for many reasons. The number of competition games and training sessions varies from one year to another, and from one team to another. Also, not every player participates in every competition or training session. In summary, using the prevalence of injury can sometimes be misleading.

2.2.1.2 Differences among sports types

The prevalence and incidence of sports injuries among different sports types and levels have not been described clearly in the literature (Lubetzky-Vilnai, Carmeli, & Katz-Leurer, 2009). A few studies have reported the prevalence and incidence according to the type and level of sport, and location of injuries. Baarveld, Visser, Kollen, and Backx (2011) reported that 58% of sport-related injuries occurred during organised sports sessions, and the rest happened during non-organised or school activities. Moreover, they indicated that 41% of recorded injuries occurred among those who practised sports activities for 0–3 hours/week, 32% in those who practised between 3 and 6 hours a week, and 6.5% for those who practised for more than 6 hours per week. In the same study, most injuries occurred in football, running/jogging, fitness, volleyball, speed skating, tennis, field hockey and walking. Most injuries (76%) were located in the lower limb extremities. Injuries in the knee joint represent 24.7% of all injuries in the upper and lower extremities; those in the ankle joint represent 18.8% of injuries.

In another study, 12 months of injury data from 68 sports centres with a total of 457 participants found the injury prevalence to be 41.6% (Lubetzky-Vilnai et al., 2009). The injury rate per 100 hours of exercise was 22.6 of all subjects. Football has a higher rate and percentage of sports injuries than sports such as hockey, volleyball, handball, basketball, rugby, cricket, cycling, boxing and swimming (Wong & Hong, 2005).

2.2.2 Knee injuries

Athletes' injuries, which occur without physical contact, are referred to as non-contact injuries (Yu & Garrett, 2007). There are many different definitions of sports injury in the literature (Wong & Hong, 2005), but there is no ideal definition as each has advantages and disadvantages (Waldén, 2007). According to the literature, there are two common types of definition: one based on the time loss, and the other on the need for medical attention. Waldén (2007) reported that in most studies, the time loss has been used to define a football injury that encompasses missing at least one training session or match, the next training session or match, the next day or the next two days. Also, he found that the 'medical attention' definition has been used recently but not in elite football exclusively. To sum up, determining the injury type and definition is important before investigating the injury risks and possible solutions for prevention.

2.2.2.1 Prevalence & Incidence

In both sexes, lower limb injuries account for 50-75% of sports injuries among different types of sports and playing levels (Hootman et al., 2007; Powell & Barber-Foss, 2000; Rauh et al., 2007). Louw et al. (2008) found that knee injuries represent about 10-25% of sports injuries in active adolescents. Specifically, injuries to knee ligaments are very common. Gianotti et al. (2009) reported that the incidence rate of knee ligaments per 100,000 person-years was 1,147.1 for non-surgical ligaments injuries, 36.9 for anterior cruciate ligaments surgeries, and 9.1 for other surgeries in the general population in New Zealand. In particular, the most significant amount of time loss in sport occurs in anterior cruciate ligament (ACL) and patellofemoral joint (PFJ) injuries (Starkey, 2000). Complications from knee injuries include developing osteoarthritis, being unable to return to the sport and thus ending the player's career, or having to change employment (Myklebust, Holm, Maehlum, Engebretsen, & Bahr, 2003; Utting, Davies, & Newman, 2005). Also, after injury, athletes have been found to suffer from psychological consequences like depression, anxiety, lack of confidence, and fear of sustaining a new injury (Ardern, Taylor, Feller, & Webster, 2013; Ardern, Taylor, Feller, Whitehead, & Webster, 2013). These physical and psychological complications give more reason to focus on ACL and PFJ risk factors when studying global knee injuries.

ACL injury is catastrophic for an athlete, due to the extended period of time-loss away from participation. It might also result in the athlete being unable to return to the same level of performance as before the injury. For instance, 42% of Norwegian elite handball players either could not return to sport at all, or returned at a lower level of performance after ACL reconstruction (Myklebust et al., 2003). More than 50% of Swedish female football players did not return to sports activities after they had undergone ACL reconstruction. Only 15% of players claimed that they returned to their pre-injury level of performance (Lohmander, Ostenberg, Englund, & Roos, 2004). Shah, Andrews, Fleisig, McMichael, and Lemak (2010) found that 37% of players of American football who had ACL reconstruction surgery could not return to play at all. Moreover, PFPS has similar consciousness of physical and psychological factors that affect the level of performance after injury. A follow up study of PFPS injured athletes found that the symptoms could persist at an average of 5.7 year (Blond & Hansen, 1998). In addition to that, they may present with functional limitation and deficit in lower limb strength and running mechanics (Esculier et al., 2018).

The incidence rate of ACL injuries is low at 0.1–0.3 per 1,000 athlete exposures, according to many published studies that show some dependence on the level and type of sports played (Gianotti et al., 2009; Gwinn et al., 2000; Quisquater et al., 2013). Additionally, the PFPS incidence rate is about 1.09 injuries per 1,000 athlete exposures, which is greater than the incidence rate of ACL injuries (Myer et al., 2010). This low rate might mistakenly suggest that this is a small problem compared with common sports injuries. However, a significant number of non-contact knee injuries, long time-loss spent away from the sport, increased risk of osteoarthritis, and high risk of losing a career make these among the most serious sports injuries.

2.2.2.2 ACL, Anatomy and Function

The ACL is one of the important structures of the knee (see Figure 2:1). The ACL plays an important role in reducing the likelihood of meniscal pathology by preventing the anterior translation of the tibia on the femur while allowing a normal knee action (Domnick, Raschke, & Herbort, 2016). The ACL stretches medially from the anterior part of the tibia, reaching a curved area on the posteromedial aspect of the lateral femoral condyle (Markatos, Kaseta, Lallos, Korres, & Efstathopoulos, 2013). The ACL plays a significant role in knee biomechanics. It is essential to ensure that dynamic stability of the knee joint is maintained to prevent hyperextension movement, which might occur during hopping, landing, cutting and pivoting manoeuvres (Macauley, 2006). The role of the ACL is to prevent the anterior translation of the tibia (Markatos et al., 2013). It also works as a stabiliser against the internal rotation of the tibia and knee valgus (Buoncristiani, Tjoumakaris, Starman, Ferretti, & Fu, 2006; Markatos et al., 2013). The ACL absorbs about 75% of the anterior translation load during full knee extension, and about 85% of the load between 30° and 90° of flexion (Butler, Noyes, & Grood, 1980). The ACL has anteriomedial and posteriolateral bundles (Markatos et al., 2013). Regarding its function, the anteriomedial fibres become rigid during knee flexion while the posteriolateral fibres exhibit tension during knee extension. It has been reported that ACL anterior bundles can bear higher maximum strain and stress load than the posterior bundles (Butler et al., 1992). The maximum tensile strength of ACL is approximately 1,725 ± 270 N but differs with age and repetitive loads (Markatos et al., 2013; Miller, 2000). As the magnitude of the anterior shear force increases, the in situ force of the ACL increases (Dargel et al., 2007). The ACL average length is about 38 mm with an average width of 11 mm (Markatos et al., 2013). The main blood supply comes from the middle geniculate artery and the innervation is from the tibial nerve (Markatos et al., 2013). The ACL contains many mechanoreceptors that play an important role in joint proprioception function (Adachi et al., 2002; Markatos et al., 2013).

Figure 2:1 Knee structures: ACL, PCL, MCL and LCL (Petersen & Tillmann, 2002)

2.2.3 Role of movements in knee injuries

2.2.3.1 Mechanism of knee injury

The knee is one of the major weight-bearing joints, and it connects two of the longest bones in the human body. These two facts make the knee one of the joints most susceptible to injury due to the multidirectional forces, which cause shear, and torsion loads (Bartlett & Bussey, 2012). Messier et al. (2008) reported that behavioural and physiological risk factors are believed to interact with potential biomechanical mechanisms (knee joint forces and moments) to cause knee injury. Therefore, it is important to study the risk factors of knee injuries and the associated mechanism. Examining the risk factors of knee injury is very difficult because of the complexity of how these factors interact. This makes studying isolated risk factors practically impossible, and difficult to determine the relative contributions of each factor (Bartlett & Bussey, 2012).

2.2.3.1.1 Mechanism of Anterior Cruciate ligament injury

To reduce the occurrence of ACL injury, which is one of the most serious and problematic sports injuries, it is crucial to understand the injury mechanism. As most ACL injuries are mostly non-contact injuries and therefore potentially avoidable, it is even more important to understand the injury mechanism.

At the start of investigating ACL injuries, researchers used a questionnaire to understand the ACL mechanism. The participants were asked to report the cause and mechanism of their injuries; most reported that their injuries happened during decelerating activities, such as cutting (changing direction), unilateral and bilateral landing (Boden, Dean, Feagin, & Garrett, 2000; Myklebust et al., 1998). This method has many limitations, so provides the lowest level of evidence. Each participant's ability to remember the injury mechanism is one of the critical limitations. However, evidence from the videotape footage analysis method supported the idea that links the cutting and landing movements to most non-contact ACL injuries (Boden et al., 2000; Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). In addition, the ACL injuries examined in these studies occurred during the decelerating phase of these movements. The results showed that injured athletes land with the hip flexed slightly, adducted and internally rotated, the knee slightly flexed with tibial external rotation and evidence of a knee valgus collapse.

More recently, Koga, Nakamae, et al. (2010) used a new technique to study the ACL injury mechanism, known as the model-based image-matching method. Even give its limitations, this method was the most accurate and detailed for the ACL mechanism at the time. More importantly, it confirmed previous findings that the knee flexion angle is minimal (< 25°) with knee external rotation and valgus.

2.2.3.1.2 Mechanism of Patellofemoral joint injury

PF joint injury is dissimilar to ACL injury because it is an insidious and gradually worsening onset of non-specific pain as defined by Fulkerson (2002), where the ACL injury has a specific mechanism and a traumatic onset. Maltracking of knee patella during movement is considered to be the common cause of PFPS (Powers, 2003). The increase in abnormal contact pressure of the PF joint (PFJ) over time due to maltracking could lead to pathology causing PFPS (Barton, Levinger, Crossley, Webster, & Menz, 2012). Recently, more research about the PFJ contact pressure showed that increases in hip adduction, hip internal rotation and external tibial rotation will reduce the PFJ contact area, and increase the contact pressure at the same time (Lee, Anzel, Bennett, Pang, & Kim, 1994; Salsich &

Perman, 2007). During walking and squatting tasks, patients with PFPS show higher PFJ pressure, which is due to the reduction of the PFJ contact area (Brechter & Powers, 2002; Keyak et al., 2011). This abnormal change in PFJ contact area might result in articular cartilage damage over time (Salsich & Perman, 2007). However, that cannot be the cause of pain because it is not innervated tissue (Biedert, Stauffer, & Friederich, 1992). In fact, the subchondral bone is believed to be the source of the PFJ pain (Biedert & Sanchis-Alfonso, 2002), a belief supported by the advanced degeneration in patella cartilage among PFPS patients (Farrokhi, Colletti, & Powers, 2011).

2.2.4 Non-contact knee injuries risk factors

2.2.4.1 Anatomical risk factors

- Femoral intercondylar notch, and ACL sizes:

The notch size is important because it contains the ACL. Many studies have investigated the relationship between femoral intercondylar notch size and ACL injury. There are conflicting results in the literature regarding this relationship (Harner, Paulos, Greenwald, Rosenberg, & Cooley, 1994; LaPrade & Burnett, 1994; Shelbourne, Davis, & Klootwyk, 1998; Uhorchak et al., 2003).

Munro (2012) suggested that this difference is probably because of the use of two different notch size calculation measures: femoral intercondylar notch width and femoral intercondylar notch width index. Shelbourne et al. (1998) recommended the use of femoral intercondylar notch width rather than the femoral intercondylar notch width index, because the notch width index depends on an individual's height. A small intercondylar notch width was found to be related to ACL injury (Uhorchak et al., 2003), although the reason for this relationship is not well understood. Uhorchak et al. (2003) suggested that the reason could be the impingement of the ACL to the intercondylar notch wall or the small size of the ACL itself, which will have less material strength than a larger ACL.

2.2.4.2 Hormonal risk factors

There is no significant difference in ACL injury rate, knee valgus angle and lower limb muscle strength between boys and girls before puberty (Barber-Westin, Noyes, & Galloway, 2006; S. D. Barber-Westin, Galloway, Noyes, Corbett, & Walsh, 2005; Ford, Shapiro, Myer, Van Den Bogert, & Hewett, 2010; Hewett, Myer, & Ford, 2004). However, post-puberty, the neuromuscular characteristics and the ACL injury rate differ between men and women. Women have demonstrated a significantly greater knee valgus motion and lower muscle power and strength after maturation (Barber-Westin et al., 2006; Ford et al., 2010; Hewett et al., 2004; Wikholm & Bohannon, 1991). In contrast, men demonstrate increased muscle strength but no changes in knee valgus motion (Barber-Westin et al., 2006; Ford et al., 2010; Hewett et al., 2004; Wikholm & Bohannon, 1991). The increase in muscle strength of men helps to counteract the biomechanics and neuromuscular control (NMC) changes. The difference in NMC between men and women may contribute in part to the different injury rates between sexes (Hewett et al., 2004). Therefore, as there is no change in male knee valgus motion post-puberty, the hormonal factor appears to have a minimal effect on the injury rate. However, this assumption has not yet been investigated.

2.2.4.3 Psychological risk factor

There is only limited scientific research on the effect of psychological factors on sports injuries (Junge, 2000). Those research articles are usually out of date, and have heterogeneous designs, different criteria and different evaluation strategies (Junge, 2000). According to Coddington and Troxell (1980), the chance of being injured might be affected by the athletes' mental and emotional state. Andersen and Williams (1988) have developed a model based on stress theory and injury to explain the effect of psychological factors on sports injuries. They described the effect of personality, history of stressors and coping resources on injury and how these factors interact with each other. They also described some intervention strategies such as cognitive restructuring, thought stoppage, confidence training and relaxation skills that might help to reduce the chance of getting injured.

Hardy (1992) reported that athletes have described contributory factors to stress such as being unprepared to play and losing internal control, fear of failure, and worrying about the views of the coach and fans. Other studies have mentioned that stress has a great impact on athletes' performance. It has been found that emotional stress increases the blood flow (Wilkins & Eichna, 1941), which is believed to be due to adrenaline, which has large impact on muscle contraction (Cooper, Edholm, & Mottram, 1955). The increase in adrenaline during physical activity changes the muscle contraction and decreases the duration of slow twitch phase in calf muscle (Marsden and Meadows (1970). This effect is caused specifically and directly by adrenaline and not by other factors (Marsden & Meadows, 1970). Therefore, the psychological factor is one of the secondary factors that relate to sports injury. However, newer research is needed to understand the importance of psychology on the prevalence of sports injuries.

2.2.4.4 Performance and training risk factors

There is no evidence that there is any training regime or specific exercise could be a direct risk factor for non-contact ACL and PFPS injuries. However, there are growing evidence suggesting that overtraining could cause fatigue and therefore causing altered movement pattern, which will result in to non-contact ACL or PFPS injuries (Tamura et al., 2016). In ACL, it has been found in vivo study that sub-maximal repetitive loading could cause the ACL ligament fatigue rupture (Wojtys, Beaulieu, & Ashton-Miller, 2016). Also, the PFPS has been identified as an overuse injury which support the idea of the over playing and training as a contributing factors in injuries (Hreljac, Marshall, & Hume, 2000). Therefore, to prevent these injuries, the goal would be to maintain the homeostasis of the ligament by limiting the rate of ligament micro-damage accumulation to be less than or equal to its rate of remodelling (Wojtys et al., 2016).

2.2.4.5 Biomechanical risk factors

Knee joint movements occur in all three anatomical planes; sagittal, frontal and transverse. These movements occur between the femoral condyles and tibial plateau with six degrees of freedom (three rotations and three translations allowing for 12 directional motions) (Munro, 2013). The abduction and adduction movements occur in the frontal plane; flexion and extension in the sagittal plane; and internal and external in the transverse plane. Knee joint translation occurs in the sagittal plane anteriorly and posteriorly; in the frontal plane medially and laterally; and in the transverse plane via compression and distraction (Munro, 2013).

2.2.4.5.1 Frontal plane movements

Knee valgus and hip adduction angles have been studied as the primary motions in the frontal plane, which contribute to non-contact knee injuries. Other motions such as trunk lateral shifting have been found to have some relationship to non-contact knee injuries. These motions are observed to have a relationship with the prediction of ACL, PFPS. Here, we will try to understand the relationship between these motions and those injuries.

- Knee valgus

Knee valgus motion, which happens in the frontal plane, is also known as knee abduction motion. The relationship between knee valgus and knee injuries has been studied extensively. Increased knee valgus angles and moments are found to be related to and to predict anterior cruciate ligament and patellofemoral joint (PFJ) injuries (Hewett et al., 2005;

Holden, Boreham, Doherty, & Delahunt, 2017; Myer et al., 2010; Myer et al., 2015; Shimokochi & Shultz, 2008). Knee valgus loading rarely occurs in isolation, which means that when combined with transverse plane knee loading, it will affect the ACL loading pattern (Shimokochi & Shultz, 2008). It is therefore difficult to study such motion in isolation of other motions in different planes. High knee valgus angles does not have sufficient load to injure the ACL without first causing injury to the medial collateral ligament (Bendjaballah, Shirazi-Adl, & Zukor, 1997; Mazzocca, Nissen, Geary, & Adams, 2003). During ACL injury episodes, the valgus collapse pattern has been reported (Krosshaug et al., 2007; Olsen et al., 2004). In a prospective study using the 3D system of Hewett et al. (2005) on 205 women's soccer, basketball and volleyball players, nine subjects suffered non-contact ACL injuries. Those injured players had significantly greater knee valgus angle and moments during a bilateral drop vertical jump task. The ACL-injured players were found to have significantly greater knee valgus of 8.4° at initial contact and greater 7.6° peak valgus than the uninjured players. Also, ACL-injured players had significantly greater knee moments by 26.9 Nm. In a study of cadaveric knees, a 10 Nm force caused a significant increase in ACL load (Fukuda et al., 2003). Fukuda et al. (2003) found that an addition of 10 Nm of valgus torque at 15°–45° knee flexion angle increased the ACL load to 35–40 N compared with the load when only 5 Nm was added. Therefore, it is possible that the 26.9 Nm moment that was reported in the study by Hewett et al. (2005) could increase the load by almost 100 N (Ghulam, 2016), and is very likely to be a contributing risk factor to injury.

Myer et al. (2010) in a prospective study found that high knee valgus load during running and landing tasks can predict PFPS. In another prospective study, Stefanyshyn, Stergiou, Lun, Meeuwisse, and Worobets (2006) found that PFPS injured runners have greater knee valgus impulse than those without injury. Knee valgus impulse was calculated as the amount of knee valgus moment demonstrated over time. Myer et al. (2015) suggested that knee abduction load during landing is associated with a greater risk of developing PFPS. This relationship between knee valgus motion and PFPS might be due to increased lateral patellar displacement that is observed during knee valgus motion (Noehren, Barrance, Pohl, & Davis, 2012). The findings from retrospective studies were not consistent with those from prospective studies. The retrospective studies found no difference in knee valgus between PFPS sufferers and asymptomatic players (Bolgla, Malone, Umberger, & Uhl, 2008; Dierks, Manal, Hamill, & Davis, 2008). However, Munro (2013) argued that this could be due to pain position avoidance in PFPS sufferers. Therefore, most previous studies showed a potential relationship between knee valgus motion and non-contact ACL or PFPS injuries. However, there has been no retrospective or prospective study to investigate the male population, so it not clear that there will also be a relationship between knee valgus motion and non-contact ACL or PFPS injuries in male players. More studies are needed to cover this population.

- Hip adduction

Even if it is not always distinct, PFPS patients usually have greater hip adduction angle than healthy people during some athletic tasks (Bolgla et al., 2008; Dierks et al., 2008; McKenzie, Galea, Wessel, & Pierrynowski, 2010; Nakagawa, Moriya, Maciel, & Serrao, 2012; Willson et al., 2008; Willson & Davis, 2008, 2009). Hip adduction motion is assumed to contribute to knee valgus angle and moment, which might result in PFPS, ACL and MCL injury as explained in previous section of 'Knee valgus'. This relationship has not been investigated (Munro, 2013), although hip adduction has been found to be correlated with knee valgus via 2D FPPA (Hollman et al., 2009; Willson & Davis, 2008). Increased hip adduction also leads to high Q angle, which usually results in patellar displacement, which has been defined as one of the PFPS risk factors (Powers, 2003). Hewett et al. (2005) noted that increases in hip adduction moment showed a strong correlation with knee valgus moment in ACL-injured women compared with uninjured women. In some studies, high hip adduction angle was detected during ACL injury episodes (Boden et al., 2000; Krosshaug et al., 2007). The hip adduction angle in PFPS subjects was significantly greater than in asymptomatic subjects by 2.4°–5.5° (McKenzie et al., 2010; Willson & Davis, 2009). Even in studies where no significant difference was reported, the PFPS sufferers exhibited greater hip adduction values (Munro, 2013). However, so far, no relationship between hip adduction motion and ACL or PFPS has been found prospectively (Boling et al., 2009). Future prospective studies are needed to examine the relationship between hip adduction motion and knee injury.

- Trunk lateral shifting

Ipsilateral trunk shifting has been found to increase knee valgus moment by changing the ground reaction force vector to pass laterally to the knee joint centre (Hewett, Torg, & Boden, 2009). Powers (2003) concluded that a higher valgus moment at the knee might increase the dynamic quadriceps angle, which will increase the lateral force acting on the patella, which may result in greater stress on the lateral compartment of the patellofemoral joint. Nakagawa, Maciel, and Serrao (2015) confirmed that individuals with PFPS had higher peak ipsilateral trunk lean than the control group. Also, ipsilateral trunk shifting due to weak hip abductors was found in patients with PFPS, which might be interpreted as the body compensating for the weak hip abductors (Boling, Padua, & Alexander Creighton, 2009). Zazulak, Hewett, Reeves, Goldberg, and Cholewicki (2007) found that factors associated with core stability could predict the risk of knee, ligament and ACL injuries with high sensitivity and moderate specificity in female but not in male athletes. Therefore, this might not be a good factor for investigating the risk factors for knee injury in male athletes. Hewett et al. (2009) have supported this idea by emphasising the importance of lateral trunk and valgus knee motions on ACL injury mechanism in female athletes specifically.

2.2.4.5.2 Sagittal plane movements

- Anterior tibial shear

The quadriceps contraction causes large anterior shear forces at angles close to full extension (Pandy & Shelburne, 1997). This position was observed during ACL injury episodes (Koga, Krosshaug, et al., 2010). Moreover, quadriceps effects to cause anterior tibial shear decrease as knee flexion angle increases, due to the change in force line (Hashemi et al., 2011). In contrast, contraction of the hamstring muscle may help to decrease the anterior shear force, which may prevent ACL injury (Li et al., 1999). Moreover, the distribution of landing forces on the ankle and hip will help to reduce the load on ACL. Therefore, the anterior tibial shear alone is unlikely to cause ACL injury (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006).

- Knee flexion angle

As explained previously, ACL injury risk is greatest at angles closer to full extension (Li et al., 1999; Pandy & Shelburne, 1997). Also, the knee flexion angle during landing from different tasks was found to be 5–10° less in women than in men (Huston, Vibert, Ashton-Miller, & Wojtys, 2001; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001). However, Hewett et al. (2009) found no significant differences in knee flexion angle between female and male ACL-injured subjects or between female ACL-injured subjects and female controls. Therefore, it is less likely for knee flexion angle to be the reason for higher rate of female knee injuries.

- Vastus Medialis Obliquus muscles

A weakness of the quadriceps muscles is believed to affect the alignment of the patella, especially the vastus medialis (VM) and the vastus medialis obliquus (VMO). Neptune, Wright, and van den Bogert (2000) reported that decreases in strength of VMO muscle increase lateral patella shift and PFJ load. Moreover, they found that delay in VMO contraction by 5 ms could increase the peak of lateral PFJ load significantly. A prospective study found that subjects who developed PFPS had a significant delay in VMO by 1.67 ms compared with those who did not (Van Tiggelen, Cowan, Coorevits, Duvigneaud, & Witvrouw, 2009). However, there are also contradictory findings in the literature. Retrospective and prospective studies found no significant difference in timing between VMO and VL contraction in the PFPS group and the asymptomatic group (Cavazzuti, Merlo, Orlandi, & Campanini, 2010; Witvrouw, Lysens, Bellemans, Cambier, & Vanderstraeten, 2000). However, the functional value of the tasks (a static toe raise exercise and knee jerk reflex activated via a patella tendon tap) used by Van Tiggelen et al. (2009) and Witvrouw et al. (2000) have been questioned by Munro (2013). Munro also raised some concerns about whether the VMO delay can be clinically significant and measurable using the surface EMG. Therefore, more studies are needed with more common functional tasks. However, it can be argued that the VMO factor alone will have a minimal effect on predicting ACL and PFPS injuries.

- Iliotibial Band (ITB)

The iliotibial band (ITB) is a continuation of the tensor fascia lata viewed as a band of dense fibrous connective tissue that passes over the lateral femoral epicondyle and attaches to the lateral side of the patella (via the retinaculum) and Gerdy’s tubercle on the anterolateral aspect of the tibia (Fairclough et al., 2006; Terry, Hughston, & Norwood, 1986). The ITB is a lateral stabiliser of the patella (Hudson & Darthuy, 2009). In cadaveric knees, (Kwak et al., 2000) found that change in ITB kinematics alters patellar kinematics and contact. This study showed that loading of the ITB causes lateral patella translation, which has previously been linked to PFJ load and increased probability of PFJ pathology (Hudson & Darthuy, 2009). Ober's test is commonly used to assess the flexibility of the ITB (Park, Kang, Choung, Jeon, & Kwon, 2016). It has also been used as an indirect measure of ITB length (Herrington, Rivett, & Munroa, 2006; Hudson & Darthuy, 2009; Kang, Choung, Park, Jeon, & Kwon, 2014). Herrington et al. (2006) found a moderate correlation between patellar position and ITB length using the modified Ober's test where the tested leg was bent to 90° of knee flexion. Hudson and Darthuy (2009) and Puniello (1993) reported that PFPS sufferers had a significantly shorter ITB length using the modified Ober's test. These results suggest that the ITB length might be one of the factors that contribute to PFPS development. However, prospective studies are needed to determine whether ITB shortness is a cause or effect of PFPS, as all studies are retrospective. Moreover, it is not confirmed that ITB shortness alone is the reason for patellar lateral transition (Kang et al., 2014). Therefore, ITB might play a minimal role in predicting the PFPS injury.

- <u>Foot pronation</u>

During pronation, the calcaneous everts and the head of the talus slides medially and inferiorly resulting in medial rotation of the talus. As a result, the tibia rotates internally (Powers, Chen, Reischl, & Perry, 2002). It has been hypothesised that in order for the knee to extend while the tibia is internally rotated, the femur must also internally rotate, leading to more hip adduction (Tiberio, 1987) and more lateral PFJ contact pressure (Lee et al., 1994). A recent study found that the increase in foot pronation might result in lower limb musculoskeletal injury due to the resulting biomechanical changes (Resende, Deluzio, Kirkwood, Hassan, & Fonseca, 2015).

In individuals with PFJ syndrome, greater rearfoot eversion has found to be correlated with greater hip adduction during gait (Barton et al., 2012). The authors suggested that this relationship between foot and hip kinematics might lead to increased pronation being a risk factor for PFPS. However, the few studies that investigated the association between foot pronation and PFPS have reported conflicting results (Boling et al., 2009; Dierks et al., 2008; Duffey, Martin, Cannon, Craven, & Messier, 2000; Powers et al., 2002). In retrospective studies, Powers et al. (2002) and Dierks et al. (2008) found no difference in foot pronation between asymptomatic and PFPS groups whereas Duffey et al. (2000) reported a significant difference between the two groups. Moreover, in the only prospective study, Boling et al. (2009) reported that the participants who suffered PFPS were found to have a significant increase in navicular drop as a static measure for pronation.

The two studies that found a link between the foot pronation and PFPS (Boling et al., 2009; Duffey et al., 2000) used a static measures (navicular drop and arch height), which might not provide sufficient information about the dynamic pronation and its relation to PFPS injury. Prospective studies are needed to examine the relationship between the dynamic foot pronation and PFPS injury.

2.2.4.5.3 Transverse plane movements

- Hip internal rotation

The hip internal rotation has been mentioned as one of the contributing factors to dynamic knee valgus (Graci & Salsich, 2015; Ireland, 1999; Powers, 2003, 2010), which has been linked to ACL and PFPS injuries (Hewett et al., 2005; Holden et al., 2017; Myer et al., 2010; Myer et al., 2015; Shimokochi & Shultz, 2008). When the femur rotates internally, the tibia will rotate externally, which can cause ACL impingement, increasing the strain and risk of injury (Fung, Hendrix, Koh, & Zhang, 2007). In contrast, in an in vivo study, a restriction in hip internal rotation due to femoroacetabular impingement (FAI) was found to be significantly associated with increased risk of ACL injury in ipsilateral or contralateral knee (Bedi et al., 2016).

Regarding the PFPS, the increased hip internal rotation can also alter patella alignment (Powers, 2010), and increase PFJ forces by increasing the pressure on lateral patellar facet (Lee, Morris, & Csintalan, 2003). During a single leg squat (SLS), sufferers of PFPS were shown to have greater hip internal rotation with greater lateral patellar displacement (Souza, Draper, Fredericson, & Powers, 2010). Moreover, some studies found a greater peak hip internal rotation during single leg squat, running, drop-jump and step-down tasks than in the healthy group (McKenzie et al., 2010; Nakagawa et al., 2012; Souza et al., 2010; Souza &

Powers, 2009a, 2009b). In contrast, other studies found no difference between PFPS patients and the asymptomatic group in hip internal rotation (Bolgla et al., 2008; Willson & Davis, 2009). A prospective study found that those who developed PFPS found had a similar hip internal rotation angle to uninjured subjects (Boling et al., 2009). Also, the hip internal rotation could only predict the development of PFPS within a regression model combined with knee flexion, navicular drop and vertical ground reaction force (Boling et al., 2009). These conflicting results suggest the need for more prospective studies to understand the relationship between hip internal rotation and non-contact knee ligaments injury. Also, it is important to know whether this relationship exists only among women or can be generalised to include men as well.

- <u>Tibial rotation</u>

External rotation of the tibia was found to increase the ACL strain significantly (Markolf et al., 1995), and might cause ACL impingement (Fung et al., 2007). Also, it resulted in more lateral patellar displacement (Noehren et al., 2012), as a decreased PFJ contact area caused more PFJ pressure (Lee et al., 1994; Lee et al., 2003; Shultz, Dudley, & Kong, 2012). Moreover, the external tibial rotation theoretically can increase the Q angle (Powers, 2003), resulting in more PFJ contact pressure. However, more recent studies found that the Q angle does not differ between those who suffer PFPS and those who do not (Almeida et al., 2016; Silva et al., 2015). However, internal rotation of the tibia causes thinning of the medial side of the PFJ compartment (Salsich & Perman, 2007). Both external and internal tibial rotation have been observed during ACL injury episodes (Olsen et al., 2004). However, despite the evidence in some studies that tibial rotation increases the loading on ACL and PFJ, no research has examined the impact of tibial rotation on injury risk (Munro, 2013).

2.2.5 Summary

In summary, knee injuries are one of the most serious common sports injuries. The literature on injury risk factors suggests that forces caused by sagittal plane mechanisms may have been overestimated with regards to their potential to cause ACL injury (Munro, 2013). There is therefore a need for more prospective research on the frontal plane to investigate knee injuries and the related movement. McLean, Huang, Su, and van den Bogert (2004) reported that biomechanical modelling has suggested that frontal plane loading is more important in knee injuries. The frontal plane is therefore the best plane to investigate risk factors for knee injuries.

2.3 Role of movements variability

2.3.1 Introduction

Variability in movement is seen in all movement tasks and occurs both between and within individuals (Bartlett, Wheat, & Robins, 2007; Preatoni et al., 2013; Smith, Christensen, Marcus, & LaStayo, 2014). Certain amount of movement changes can be detected when the same action has been repeated (Bartlett et al., 2007). Movement variability is thought to be inherited in motor performance and could be due to the complexity of the neuromusculoskeletal system (Bartlett et al., 2007; Preatoni et al., 2013). In the last ten years, the movement variability has gained a great deal of interest specifically in the sports and clinical biomechanics communities (Arshi, Mehdizadeh, & Davids, 2015; R. Bartlett, Bussey, & Flyger, 2006; Nordin & Dufek, 2017; Pollard, Stearns, Hayes, & Heiderscheit, 2015; Preatoni, Ferrario, Dona, Hamill, & Rodano, 2010).

Usually, the movement is described by the average of repeated actions with no one looking at the movement variability (the variability between repetitions) and what it suggests about the actual performance. The aims of sports biomechanics are to improve the capabilities of athlete performance, technique proficiency and consistency (Preatoni et al., 2013), particularly for individuals. It is critical that sports biomechanics pursue injury prevention programmes based on the athletes' biomechanical demands (Preatoni et al., 2013). The movement variability in sports should not be investigated for reliability only, but should be considered as a potential source of information for the analysis of monitoring of athletes' biomechanical performance (Preatoni et al., 2013). Until the last decade, movement variability within individuals has been recognised as 'noise' due to errors in sensory information and motor output commands, changes in environmental condition, or errors in measuring and analysing procedures (Bartlett et al., 2007; Konig, Taylor, Baumann, Wenderoth, & Singh, 2016; Preatoni et al., 2013). There are two types of movement variability: performance variability, which is the variability in how the movement was obtained; and outcome variability, which is the variability in what has been achieved (Preatoni et al., 2013).

Studies have investigated the variability of athletic tasks variables (Arshi et al., 2015; Bradshaw, Maulder, & Keogh, 2007; Diss, 2001; Fleisig, Chu, Weber, & Andrews, 2009; James, Dufek, & Bates, 2000; Lees & Bouracier, 1994; Nordin & Dufek, 2017; Preatoni et al., 2010; Queen, Gross, & Liu, 2006; Rodano & Squadrone, 2002), and the difference in variability variables between pathological and asymptomatic subjects (Brown, Bowser, & Simpson, 2012; Konig et al., 2016; Muniz & Nadal, 2009; Pollard et al., 2015; Smith et al., 2014). However, no studies have investigated the variability differences in kinematics and kinetics variables between legs and/or over sports season (over time), and its relation to sport injuries.

Movement variability can be affected by many factors such as age, temperature, stage of season, muscle strength and flexibility, surface of play and athletic shoes. In this chapter, we will try to investigate each of these factors, and how it might affect the individual variability through the sports season. The factors have been divided into three main categories: variability over time (age, temperature and stage of season), variability due to performance (muscle strength, flexibility and warm up), and variability due to friction (play surface and athletic shoes).

2.3.2 Variability over time

2.3.2.1 Age

It is well known that older adults have more variability in motor function than young adults at low force levels, during isometric and anisometric contractions (Christou, 2011). The literature shows that there is a positional deference between the two limbs, which suggest that motor functions of the upper and lower limbs decline at different rates with age. Kwon, Baweja, and Christou (2011) reported that there are age-associated differences, which are more significant in the lower limbs than the upper limbs, especially during dorsiflexion movement. Tracy, Dinenno, Jorgensen, and Welsh (2007) found that the force variability in knee extensors is greater than the elbow flexors in older people. Moreover, the motor output variability was greater in the lower limbs among young participants who performed goal-directed contractions (Christou & Rodriguez, 2008). All these studies reported constant findings regarding variability in motor output according to age. However, this change in motor variability takes several years, so has no direct effect on players' movement variability during the course of one or two years. More specifically on the age effect, Stevenson, Hamer, Finch, Elliot, and Kresnow (2000) found that among all participants the injury incidence rate was the largest in the 26–30 age group (IR= 20.2/1000 hours), then in the 18–

25 age group, and finally in the under-18 age group. This could means older players are more susceptible to injury. However, this study included different types of sports (hockey, football, basketball and netball), and all contact and non-contact injuries.

2.3.2.2 Temperature ranges

In Europe, football teams in northern areas, which tend to be cooler, have a higher rate of injuries than teams in southern, warmer areas (Orchard et al., 2013). The only exception is the ACL injury rate, which is higher in southern Europe. In contrast, football teams in warmer areas (‘northern Australia’) have higher rates of injuries than cooler areas (‘southern Australia’) (Orchard et al., 2013). However, Orchard et al. (2013) concluded that Australian football and European football studies have common findings. These findings report that ankle sprain and ACL injuries rate are higher in warmer areas, whereas the Achilles tendinopathy injury rate is higher in cooler areas. Moreover, they added that there are large confounders when using the epidemiology to compare the injury rates of different climate zones. This could be due to the variation of football codes, length of season and levels of play between different countries in different climate zones. However, Orchard et al. (2013) suggest that the difference in injury rate between different climate zones might be due to the use of different type of grasses which are considered to have different injury rates. Also, no one has looked at the relationship between movement variability and weather.

2.3.2.3 Stage of season

Very few studies have examined the injury according to the stage of the season. Most studies reported the injury prevalence, not the incidence, so it might be misleading to compare this to the stage of the season or other studies.

An Australian study found that the incidence rate was greater during the first four weeks of the season (Stevenson et al., 2000). Over the season, this high rate declined except for the last follow-up for all sports types. Men had a greater risk (IR = 19.0/1,000 hours) than women (IR = 13.6/1,000 hours). Among all participants the incidence rate was the largest in the 26–30 age group (IR= 20.2/1,000 hours), then the 18–25 age group, and finally the under-18 age group. This study included all contact and non-contact injuries for different types of sports.

Only a few studies have reported the incidence rate of sports injuries across the season. These studies reported different incidence rates for injuries across the sports season, and across match and training time. In a four-year study of the incidence of ACL injuries, Dodson, Secrist, Bhat, Woods, and Deluca (2016) reported the highest rate of injuries during the pre-season practice and games. In another four-year study, Bradley, Klimkiewicz, Rytel, and Powell (2002) reported the same pattern of highest ACL injuries during the pre-season practice and games. Even though these studies counted both contact and non-contact ACL injuries together, it remains important to study the performance change over time and its relation to injuries and how could that contribute to injury prevention programmes. However, no one has looked at the individual kinematics variability along season, and its relation to injury.

2.3.3 Variability due to performance

2.3.3.1 Muscle strength and flexibility

Muscle strength and flexibility play a role in the movement of the lower limb extremities. Krutsch et al. (2015) reported that trunk muscles coordinate all repetitive movements in football initially. These movements include jumping, passing, running and shooting. They also found that professional players generally had greater trunk muscle strength than amateur players. However, the impact of these factors is not well understood (Krutsch et al., 2015), and might be of even lower impact when comparing players at the same level.

2.3.3.2 Warm up

Muscle stretching as part of the conventional warm up before exercise was thought to have a strong effect in preventing injuries (Shehab, Mirabelli, Gorenflo, & Fetters, 2006). However, current studies showed that stretching alone is insufficient to prevent injury (Pope, Herbert, Kirwan, & Graham, 2000; Thacker, Gilchrist, Stroup, & Kimsey, 2004; Witvrouw, Mahieu, Danneels, & McNair, 2004). More studies need to be conducted to find a clear answer for these conflicting results.

More recently, researchers have developed neuromuscular training strategies for preventing sports injuries. Herman, Barton, Malliaras, and Morrissey (2012) found that these new neuromuscular warm-up strategies such as ‘FIFA 11+ (Soligard et al., 2008) and KIPP (LaBella et al., 2011)’ are helpful in reducing the overall number of lower limb injuries. However, these findings are difficult to apply because they require the use of special training equipment. Also, additional training is needed to achieve the benefits. Moreover, none of the current neuromuscular warm-up strategies have been found to reduce lower leg and ankle injuries significantly.

Another essential point is that the football comprehensive injury-prevention programme (the F-MARC 11þ), which requires minimal equipment, has been found to reduce injuries among female players but not among males (Grooms, Palmer, Onate, Myer, & Grindstaff, 2013). However, these programmes are not commonly used across sports teams, or at least in those teams who will participate in the main study of this thesis.

2.3.4 Variability due to friction

2.3.4.1 Play surface

The play surface has been studied as one of the expected risk factors for sports injuries. The play surface has progressed from the first generation to the fourth generation of sports surfaces. First-generation turf, which consist of short fibres attached to base material, is considered to have the higher association with injuries in adults (Taylor, Fabricant, Khair, Haleem, & Drakos, 2012). Second-generation artificial turf consists of longer fibres than the first generation, with sand fill; a composite fill using rubber particles was used to develop the third-generation surfaces.

Most updated studies on professional sports level found that there is no difference in injury risk between third-generation surfaces and natural grass, with the one exception that there are more ankle sprains on artificial turf (Ekstrand, Hagglund, & Fuller, 2011; Ekstrand, Timpka, & Hagglund, 2006; Williams, Hume, & Kara, 2011). In a three-year prospective study, Bjorneboe, Bahr, and Andersen (2010) found no difference in injury risk between third-generation surfaces and natural grass. Kristenson et al. (2013) found that there is no difference in the injury rates from games. Therefore, this factor might not have much impact on lower limb injuries with the new types of artificial turf except for ankle sprain injuries.

2.3.4.2 Athletic shoes

Studies have linked non-contact injuries to the lower extremities to the footwear traction (Wannop & Stefanyshyn, 2016). However, these studies could not explain how the individual components' traction affects the joint loading.

O'Kane et al. (2016) evaluated the shoe type and field surface as episodic-specific risk factors, and found that cleats worn on grass were associated with more injuries. Renstrom (1979) found that cleated shoes are related to increased injury risk in football on first-generation turf. However, these studies did not include the most recent third- and fourth-generation turf types, which are the only surfaces used now by clubs.

2.3.5 Summary

To sum up, the factors considered in this section might not have much impact on our study. Variability over time means that many years are needed before changes are shown, and our study will last for less than one year. Also, variability due to performance is not well understood except the neuromuscular warm-up training programmes, which are not used by any of our participating teams. Furthermore, variability due to friction cannot affect the reliability of this study because it will be consistent among the participating teams. Therefore, the variability effect has limited impact on this study. It will be discussed in detail in the discussion chapter. However, separate study will assess the variability of kinematics.

2.4 Screening of knee biomechanics

2.4.1 Screening tools

After discussing the factors that affect the movement causing lower limb injuries, it is important to know how to assess these factors. Most studies use 2D and 3D motion analysis to examine the lower limb biomechanics and its relationship with injuries. Each tool has advantages and disadvantages. The 3D system has been known as the gold standard to identify athletes at higher risk of injury (Munro, Herrington, & Carolan, 2012). The between-sessions reliability of the 3D system in prospective studies is still questioned due to the error sensitivity in marker placement and skin movement (Cappozzo, Catani, Leardini, Benedetti, & DellaCroce, 1996; Ford, Myer, & Hewett, 2007).

Examining the lower limb biomechanics during athletic tasks is important in order to modify their high-risk movement patterns. Most studies use 3D motion analysis to assess the lower limb biomechanics (Blackburn & Padua, 2008; Ford et al., 2003; Hewett et al., 2005). 3D motion analysis is helpful in examining all three planes of joint motion and has been considered to be the gold standard. However, there are some concerns regarding the reliability of the 3D system especially in the transverse plane. Kadaba et al. (1989) found that between-sessions reliability is not good as within-sessions reliability. This finding was confirmed later during different athletic tasks such as running, pivoting and jumping (Ferber, McClay Davis, Williams, & Laughton, 2002; Ford et al., 2007; Queen et al., 2006; Webster, McClelland, Wittwer, Tecklenburg, & Feller, 2010). Some studies have suggested that the reason for this problem is the influence of the marker placement between one session and another (Ferber, et al., 2002; Ford et al., 2007a; Queen et al., 2006). Cappozzo, Catani, Leardini, Benedetti, and DellaCroce (1996) suggested that this problem could be due to skin movement during the examination tasks.

In addition to the lack of reliability between sessions, some studies showed different degrees of reliability among different planes of movements. The sagittal plane was found to have more accurate results (Ferber et al., 2002; (Kadaba et al., 1989), whereas the frontal and transverse planes were more sensitive to errors in marker placement (Kadaba et al., 1989). McGinley, Baker, Wolfe, and Morris (2009) found that the greatest errors were in hip and knee rotation.

The other tool that has been studied to identify people at higher risk of knee injuries is 2D. The frontal plane projection angle (FPPA) has been used for this purpose (Gwynne & Curran, 2014; McLean, Walker, et al., 2005; Mizner et al., 2012; Willson & Davis, 2008). The validity of the FPPA method in relation to 3D has been investigated during some athletic tasks (Gwynne & Curran, 2014; McLean, Walker, et al., 2005; Sorenson et al., 2015; Willson & Davis, 2008). FPPA was found to be significantly correlated with knee valgus angle in 3D during single leg drop jump landing at initial contact, which might represent the SLL (Sorenson et al., 2015). Moreover, McLean, Walker, et al. (2005) found that FPPA was significantly correlated with peak 3D knee valgus angles. Also, Willson and Davis (2008) found that 2D FPPA was significantly correlated with 3D hip adduction and knee external rotation angles. Additionally, the reliability of the 2D method was investigated within sessions and between sessions and found to have a good to excellent reliability (Munro, Herrington, & Carolan, 2012; Willson, Ireland, & Davis, 2006).

2.4.2 Measurement and Functional Performance Tests

When studying the injury risk factors, many studies have used the knee separation distance method to identify athletes who are at higher risk (Barber-Westin et al., 2006; S. D. Barber-Westin et al., 2005; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005). To assess the medial knee motion, Noyes et al. (2005) placed the markers on the centre of the patella whereas recent studies have placed the marker on the lateral femoral condyle (Noyes & Barber-Westin, 2006; Sigward, Havens, & Powers, 2011). Despite the differences in way for measuring the knee separation distance, the use of this method is limited to bilateral tasks, which does not allow for comparison between limbs. Knowing that lower limb injuries occur during single leg landings makes this a significant limitation to identify athletes who are at higher risk of injury.

In recent studies, 2D frontal plane projection angle (FPPA) was used to quantify the dynamic knee valgus during common athletic tasks (Herrington & Munro, 2010; McLean, Walker, et al., 2005; Willson & Davis, 2008; Willson et al., 2006). Females were found to have increased FPPA compared with males during single leg landing and drop jump tasks (Herrington & Munro, 2010; Willson et al., 2006), which is the same finding reported using the 3D system. Willson and Davis (2008) found that PFPS patients exhibit greater

FPPA than healthy control subjects during SLS. Moreover, female basketball players showed improvement in FPPA after completing a four-week jump-training programme (Herrington, 2011).

It is essential to ensure that the screening tool is valid and reliable in the research field. FPPA was found to be significantly correlated (r = 0.72) with knee valgus angle in 3D during single leg drop jump landing at initial contact, which might represent the SLL (Sorenson et al., 2015). Moreover, McLean, Walker, et al. (2005) found that FPPA was correlated significantly with peak 3D knee valgus angles (r = 0.58–0.64) during side step and side jump. Willson and Davis (2008) found that 2D FPPA was significantly correlated with 3D hip adduction (r = 0.32) and knee external rotation angles (r = 0.48) during SLS.

This moderate correlation between 2D FPPA and 3D variables in these studies suggests that single joint motion alone will not be sufficient to examine the lower limb biomechanics and its relationship with injuries. A combination of examining hip and knee motions will be more useful in studying this relationship (Herrington & Munro, 2010; McLean et al., 2005; Willson & Davis, 2008).

The validity of 2D FPPA has been investigated and found to be moderate across some common athletic tasks such as SLS (Willson & Davis, 2008), side-step and side-jump (McLean, Walker, et al., 2005), drop jump tasks (Mizner et al., 2012), and SLL (Sorenson et al., 2015). However, the reliability of the 2D FPPA has not been studied adequately. Willson and Davis (2008) reported the interclass correlation coefficient (ICC) value of 0.88 for within-day reliability for SLS only; Munro, Herrington, and Carolan (2012) reported the within-day and between-day in SLS, SLL and drop-jump but not the inter- and intra-rater reliability. New studies are needed to assess the 2D inter and intra-rater reliability.

Regarding the screening tasks, the drop jump task has been used widely to assess athletes who are at higher risk of ACL and PFP injuries, which found them with higher knee valgus motion and moments (Hewett et al., 2005; Myer et al., 2010). However, this task cannot distinguish between the two limbs as it is a bilateral task whereas most injuries happen to a single limb (Faude et al., 2005). However, single leg landing (SLL) may be relevant for assessment as a unilateral task. Pappas et al. (2007) and Myklebust et al. (1998) reported that, during unilateral tasks, individuals demonstrate more hip adduction and knee valgus than during bilateral tasks. Munro (2013) suggested that the demand to decelerate landing forces during the SLL ‘unilateral task’ compared with the DJ ‘bilateral task’ might suggest that the SLL task is more sensitive in identifying athletes who have dynamic knee valgus. However, this claim has not been investigated.

The SLS task has been used to assess the relationship between 2D FPPA and 3D lower limb kinematics (Willson & Davis, 2008). The SLS was found to detect the lower limb kinematics demonstrated during running (Whatman et al., 2011), and to differentiate between subjects with and without PFPS (Willson et al., 2008). Thus, the SLS may have a potential role in identifying athletes who are at higher risk of PFPS. In addition, those with increased dynamic knee valgus during SLS are more susceptible to have similar dynamic knee valgus during more complex tasks such as landing and cutting (Munro, 2013).

2.5 Gap in the Literature

The major gap in the literature is the limited number of prospective studies on the risk factors for knee injuries. No study has investigated the variability in the lower limb kinematics over the sports season, which is one of the objectives of this PhD. Football has been selected as the sport to study because it is considered to be one of the dominant type of sports globally (Walden, Hagglund, Magnusson, & Ekstrand, 2011). This means it is more important to investigate knee injuries in football for the greatest benefit to the greatest number of players. Moreover, male players are considered to constitute 82% of football players around the world (Gaulrapp, Becker, Walther, & Hess, 2010). However, most studies have been conducted on the female populations because of their higher rate of susceptibility to injury (Louw et al., 2008). Thus there is a need to investigate male players specifically. Another reason for choosing male players is the availability of professional players in sports clubs who are participating in the full sports season within easy reach of the University of Salford. The age of participants was determined according to the average age of injured football professional players in previous studies, (Walden et al., 2011); this study can therefore be generalised to the entire population of football players.

Using the 3D screening tool has some disadvantages such as the cost of the system, the cost of use, the length of time needed for data collection and analysis, the need for a trained individual to use the system, and the inability to use it outdoor or transfer it to data collection sites. These disadvantages have created a gap between research and clinical practice because assessing the players usually happens in the sports clubs and clinics where a simpler and easier tool such as the 2D system is required. Therefore, studying the 2D tool is very important due to its practicality and usefulness in clinics and sports clubs.

The SLS and SLL tasks were found to be more appropriate for assessing players who are at higher risk of knee injuries, as explained previously. Both tasks are unilateral tasks, which will help to identify the risk for each leg alone as most injuries happen to one leg only. Moreover, previous studies have examined the FPPA alone. Examining both FPPA and hip adduction angle might have more significant results, knowing that they are both key contributors to knee dynamic valgus. All previous studies have examined the lower limb biomechanics on one occasion only (at the pre season), which might not be sufficient to assess the risk of injury. This is because the injury rate is different throughout the sports season and the players' performance also varies during the season due to the factors that have been discussed previously.

2.6 PhD Aims

1. Review the literature of lower limb sport injuries mechanism and risk factors.
2. Review the literature of lower limb screening tools, which can identify the risk factors of injuries.
3. Assessing the reliability and validity of 2D video to assess SLS and SLL performance.
4. Assessing the SLS and SLL performance between legs and across season.
5. Assessing the performance-variability of individual lower limbs kinematics between legs and across season.
6. Examining the relationship between kinematic measures of lower limb joints and knee injury prevalence in male footballers, prospectively.

Chapter (3)

Methodology

Chapter 3: Methodology

2D and 3D are the standard tools that have been used to identify people at higher risk of knee injuries (Hewett et al., 2005; Myer et al., 2010; Willson et al., 2008). Each tool has advantages and disadvantages, which have been discussed previously (section 2.4.2). The 3D system has been used as the gold standard to identify athletes at higher risk of injury (Munro, Herrington, & Carolan, 2012). The 3D system has some disadvantages, which made it inappropriate for use in this study. The between-sessions reliability of the 3D system in prospective studies is still questioned due to the error sensitivity in marker placement and skin movement (Cappozzo, Catani, Leardini, Benedetti, & DellaCroce, 1996; Ford et al., 2007). In addition to the lack of reliability between sessions, some studies showed different degrees of reliability between different planes of movements. The sagittal plane was found to have more accurate results (Farber & Buckwalter, 2002; Kadaba et al., 1989; Queen et al., 2006), whereas the frontal and transverse plane movements were found to be more sensitive to errors in marker placement (Kadaba et al., 1989). McGinley et al. (2009) found the greatest errors in hip and knee rotations.

The dynamic knee valgus is the key high-risk movement associated with lower limb injuries (Hewett et al., 2005; Myer et al., 2010). Therefore, the measurement errors of the 3D system might have significant impact on its ability to identify athletes who are at higher risk of lower limb injury. Another reason for not using the 3D system is the time needed for data collection and analysis for this large screening study. Moreover, bringing subjects to the 3D facility lab is impractical due to the large number of participants and the number of test sessions.

The other tool for identifying people at higher risk of knee injuries is 2D. The frontal plane projection angle (FPPA) has been used for this purpose (McLean, Walker, et al., 2005; Mizner et al., 2012; Willson & Davis, 2008). The validity of the FPPA method in relation to 3D has been investigated during certain atheletic tasks (Gwynne & Curran, 2014; McLean, Walker, et al., 2005; Willson & Davis, 2008). FPPA was found to be significantly correlated ($r = 0.72$) with knee valgus angle in 3D during single leg drop jump landing at initial contact, which might represent the SLL (Sorenson et al., 2015). McLean, Walker, et al. (2005) found that FPPA was correlated significantly with peak 3D knee valgus angles ($r = 0.58$–0.64) during side step and side jump tasks. Gwynne and Curran (2014) found a good correlation between 2D FPPA and the 3D knee valgus (r = 0.78) during SLS. Willson and Davis (2008) found that 2D FPPA was significantly correlated with 3D hip adduction (r = 0.32) and knee external rotation angles (r = 0.48) during SLS.

Using the 3D system has some disadvantages such as the cost of the system, the cost of use, the length of time needed for data collection and analysis, the need for a trained individual to use the system, and the inability to use it outdoors or transfer it to data collection sites such as sports clubs in different cities. More important that investigating the capability of the 2D technique to identify athletes who are at higher risk of injury, will make this simpler tool more usable at sports clubs and clinics. Using and validating the 2D system will therefore be one of these thesis objectives. However, a test that is not valid is not representative of what it is trying to measure. This makes the validity study critical before any clinical or research use. Also, the test, which is not reliable, will not provide consistent measurements, and consistency is essential for reliability. Therefore, reliability and validity studies should be conducted prior to the main study.

For the screening tasks, the drop jump task has been used widely to assess athletes who are at higher risk of ACL and PFP injuries, which found them with higher knee valgus motion (Hewett et al., 2005; Myer et al., 2010). However, this task cannot distinguish between the two limbs as it is a bilateral task whereas most injuries happen to a single limb (Faude et al., 2005). Single leg landing (SLL) may be relevant for assessment as a unilateral task. Pappas et al. (2007) and Myklebust et al. (1998) reported that, during unilateral tasks, individuals demonstrate more hip adduction and knee valgus than during bilateral tasks. Munro (2013) suggested that the demand to decelerate landing forces during the SLL ‘unilateral task’ compared with the DJ ‘bilateral task’ might suggest that the SLL task is more sensitive for identifying athletes who have dynamic knee valgus. However, this claim has not been investigated.

The SLS task has been used to assess the relationship between 2D FPPA and 3D lower limb kinematics (Willson & Davis, 2008). The SLS was found to detect the lower limb kinematics demonstrated during running (Whatman et al., 2011), and to differentiate between subjects with and without PFPS (Willson et al., 2008). Thus, the SLS may have a potential role to play in identifying athletes who are at higher risk of getting PFPS. Additionally, those with increased dynamic knee valgus during SLS are more susceptible to similar dynamic knee valgus during more complex tasks such as landing and cutting (Munro, 2013).

Therefore, using SLS and SLL will be most appropriate to predict which athletes are at higher risk of lower limb injuries, because of the advantages and disadvantages of the available tasks.

3.1 2D Validity and Reliability

3.1.1 Introduction

Before embarking on the main study, which will assess the relationship between lower limb kinematics and knee injuries, and individual kinematics measured through an entire sports season, it is crucial to investigate the validity and reliability of the method and tools. Study one (A) examined the validity of the two-dimensional (2D) technique compared with the three-dimensional (3D) system; study one (B) investigated the reliability of the method within and between sessions. Intra- and inter-reliabilities were also established. Moreover, small detectable difference (SDD) values have been calculated.

3.1.2 Two-dimensional (2D) Video Validity

3.1.2.1 Background

The 3D system has been used extensively to study knee injury risk factors, and is used as a gold standard to measure lower limbs kinetics and kinematics. There are some disadvantages in using the 3D system such as the cost of the system, the cost of use, the length of time needed for data collection and analysis, the need for a trained individual to use the system, and the inability to use it outdoors or transfer it to the data collection site where it is difficult to bring some subjects to system location. These disadvantages make the system inappropriate, especially with large screening projects.

Some previous studies have investigated the validity of the 2D system in some specific tasks, as explained previously (section 2.4.2)

3.1.2.2 Purpose

The goal of this study was to determine the validity of the two-dimensional procedure to measure the kinematics of the frontal plane during single leg squat (SLS) and single leg landing (SLL) when compared to 3D measurements of the same movements.

3.1.2.3 Method

3.1.2.3.1 Participants

The characteristics of the 15 recreational participants are summarised in (Table 3:1).

All subjects who are university students have participated voluntarily. All previous reliability studies have no sample size calculation. However, Wimmer and Dominick (2003) recommended that the sample size of the reliability studies should be between 10% and 25% of the main study sample size. The main study sample size would be between 100 and 150 subjects. Therefore, the reliability study sample size will be 15 subjects, which is 10% of the main study sample size. All participants were healthy with no previous lower limb injuries or musculoskeletal complaints for the six months immediately before the study. All participants read and signed the informed consent form, which was approved by the Ethical Approval Panel at the University of Salford. Participants were tested twice on their first visit (two sessions) with a one-hour gap between sessions to assess the within-session reliability. Participants were then tested again after seven days (one session) at the same time as the first session, to assess the between-session reliability during SLS and SLL tasks. Before each session, participants were asked to warm up on a stationary bicycle to ensure that all participants are doing the test while having same physiological status. Frontal plane projection angle (FPPA) and hip add angle (HADD) were assessed using 2D digital video camera (2D analysis); three-dimensional motion analysis was used to evaluate all lower limb kinematics and kinetics simultaneously while performing SLS and SLL. The correlation between 2D and 3D measures was calculated using Pearson's correlation coefficients.

Characteristics	Gender	
	Male (N=7)	Female (N=8)
Age (years)	25.0 (±6.4)	26.6 (±3.5)
Height (cm)	171.0 (±6.7)	163.0 (±5.4)
Weight (kg)	69.7 (±10.7)	63.0 (±8.0)

Table 3:1 Participants' demographics

3.1.2.4 Procedure

3.1.2.4.1 Instrumentation

3.1.2.4.1.1 Two-dimensional technique (2D)

For each subject, hip adduction angle (HADD) and knee frontal plane projection angle

(FPPA) data were recorded for the right leg during the execution of SLS and SLL. Subjects were asked to perform three successful trials for each task, and a successful trial required the movement to occur in the field of the 2D camera. The number of 3 trails was used to prevent the learning effect when more trails are added. The videotaping recorded the subject trunk and lower limbs only. A commercially available digital video camera (Sony Handycam DCR- HC37, Sony Corp, Tokyo, Japan) sampling at 30 fps was used. The camera was placed 60 cm above the floor, 2 m anterior to the subjects' landing target, and was aligned perpendicular to the frontal plane (Herrington & Munro, 2010). Markers were placed at the midpoint of the ankle malleoli for the centre of the ankle joint, the midpoint of the femoral condyles to approximate the centre of the knee joint, and on both anterior superior iliac spines (ASIS) (Willson et al., 2006). FPPA of the knee and hip angle were measured using Quintic Biomechanics software (v26, Quintic, Sutton Coldfield, UK). FPPA was defined as the angle subtended between the line from the markers on the ASIS to the knee joint and the line from the knee joint to the ankle. The hip angle was defined as the angle between the line from the marker on the ASIS to the knee joint and line connecting both ASISs. Both FPPA and hip angle were measured at the frame, which represents the point of maximum knee flexion. This was determined as the lowest point of the squat and landing tasks. Same tester who is a physiotherapist with 9 years experience "the author of this thesis" did the full procedure except the inter-rater testing which was done by a second physiotherapist with a 15 years of experience.

3.1.2.4.1.1.1 FPPA & HADD Data Analysis

The FPPA and HADD were measured during the maximum knee flexion angle in both SLS and SLL using Biomechanics Software (v26, Quintic, Sutton Coldfield, UK). The maximum knee flexion angle was defined as the lowest point reached by the subject pelvic during squatting and landing. The analysis process started with uploading a calibration video, which was taken before the start of the subject's video recording. The calibration video is about three seconds of video recording for the calibration frame (1m * 1m), then designation was pressed to set both horizontal and vertical lines with a distance of 1m for each line. The video calibration process was repeated if the camera had moved or if the subject changed his distance from the camera. Next, to be able to play the videos in slow motion, the video analysis speed was set at 30 fps. After that, the software was ready to upload and to start analysing the recorded successful trials for that participant. The video was played until the maximum knee flexion frame was achieved for both tasks. While holding the video in the maximum knee flexion frame (as defined previously), the analysis began by drawing the lines between the markers. Starting from the ASIS to the midpoint of the knee joint (the midpoint of the medial and lateral femoral epicondyles), and then ending by the middle of the ankle mortise anatomical landmark to calculate the FPPA. Then, starting from the midpoint of the knee joint (midpoint of the medial and lateral femoral epicondyles) to the ipsilateral ASIS, then to the contralateral ASIS to calculate the HADD. The convention used for measuring the FPPA was that 180° equals straight, angles greater than 180° were considered valgus, and angles of less than 180° were considered varus. The resulting number was then recorded, and a calculator was used to calculate the final results using the following mathematical equation [180 – (the resulting number) = final result]. However, for the HADD it was straightforward with no mathematical equation needed.

3.1.2.4.1.2 Three-dimensional system (3D)

To collect biomechanical data about lower limbs a motion-analysis system comprised of ten infrared (IR) cameras (Pro-Reflex, Qualisys) with a sample frequency of 240 Hz, passive retro-reflective markers and three force platforms (AMTI, USA) sampling at 1200 Hz. Qualisys Track Manager (QTM) software was used to connect the cameras. Using the Qyalisys Pro-reflex system, calibration, data collection and 3D reconstruction of retro-reflective markers form the three stages needed to collect coordinate data.

The accuracy of the positional data that can be collected is determined by the system resolution; this is turn is dictated by the capture volume size. Therefore, it is important to identify the camera position is that ensures the blind space around the selected capture volume in the camera’s field of view is minimal (Pantano, White, Gilchrist, & Leddy, 2005; Richards, Thewlis, Selfe, Cunningham, & Hayes, 2008). In this study, the ten cameras were placed surrounding the three force platforms to ensure they could capture the variables of interest during the stance phase of SLS and SLL (Figure 3:1).

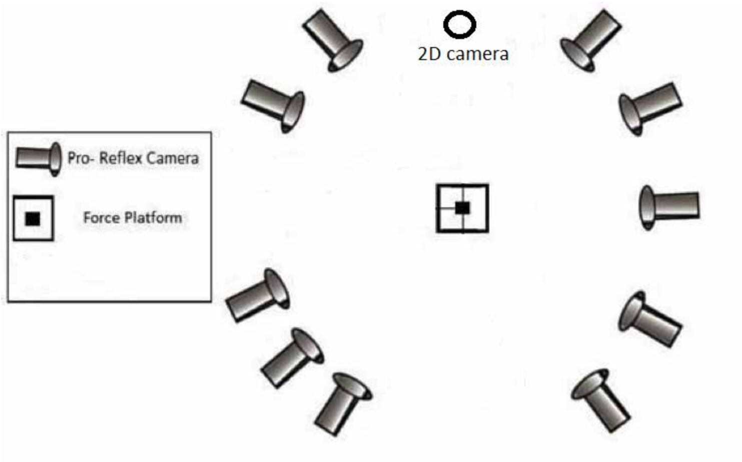

Figure 3:1 Data collection set-up

3.1.2.4.1.2.1 System calibration

The 2D image generated by each IR camera has to be converted in a 3D workplace before the coordinated data can be analysed. By using a direct-linear transformation technique, this facilitates global reference points and guarantees the generation of 3D marker position coordinates (Richards et al., 2008). The system's calibration determines the accuracy by which the position of a marker can be located in 3D space (Payton & Bartlett, 2008). Consequently, the accuracy of 3D marker coordinates and calibration based on measurements, increases with a reduction in residuals.

The static calibration of the motion-capture system and laboratory reference-frame relationship were determined using a rigid L-frame (Figure 3.2). To calibrate the volume to be used during dynamic trials handheld wands with reflective markers were positioned at each end, the distance between the wands was fixed at 750.43 mm (Figure 3:2). To standardise the calibration volume successfully, a capture time of 45 s was used. This meant that camera coverage was comprehensive, extending the field-of-view from the lower-floor level and to height and ensuring that the wand was visible to no less than two cameras. (Richards et al., 2008).

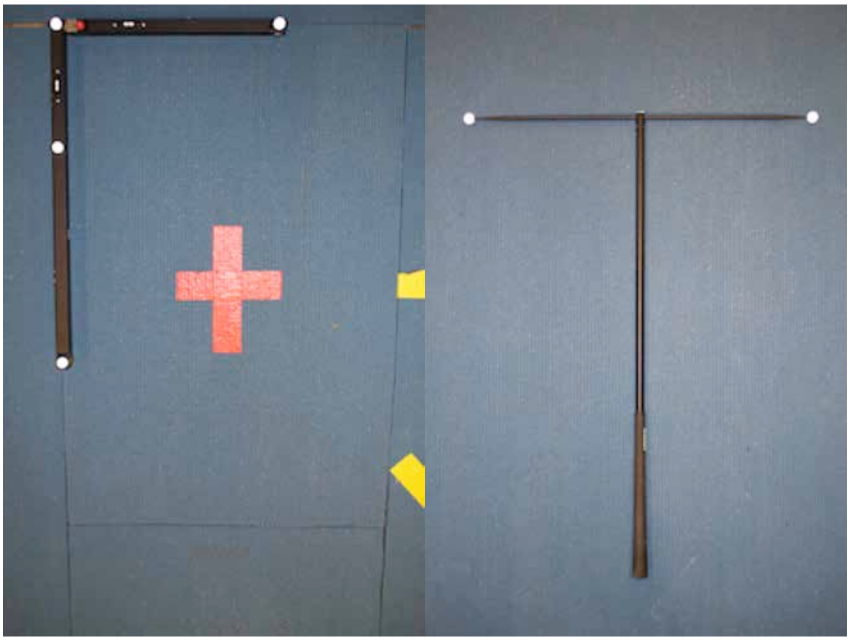

Figure 3:2 Calibration L-frame (left) and handheld wand (right).

3.1.2.4.1.2.2 Marker placement

In all data collection trials, reflective markers with a diameter of 14.5 mm were attached to the skin prior to each testing session. Hypoallergenic adhesive tape was used to attach the markers to a flat-based marker (Figure 3:3). Three non-co-linear markers were used as this enabled the orientation and position of a segment to be defined in three-dimensional space (Cappozzo, Catani, Leardini, Benedetti, & Croce, 1996). At any one time during capture, each marker was visible to no less than two cameras (Payton & Bartlett, 2008).

Figure 3:3 Cluster plates, reflective markers and adhesive tape

To characterise the centres of joints rotation and anatomical reference frame, a total of 20 anatomical markers were applied to each participant. These markers were located on anatomical landmarks, including the lateral and medial aspects of joints, as well as at the proximal and distal ends of the segment. Markers were placed on the foot on the heads of the 1st, 2nd and 5th metatarsal and the calcaneal tubercle; ankle markers were attached on medial and lateral malleolus; knee markers were placed on lateral and medial femoral condyle; thigh markers were fixed to the greater trochanter; pelvic markers were stuck to the left and right anterior superior iliac spine (ASIS), the left and right posterior superior iliac spine (PSIS) and the left and right iliac crest.

Having satisfactorily captured all the static markers, some of the anatomical markers were removed, leaving 28 markers in place for tracking (4 on ASISs and PSISs, 8 fixed to standard shoes and 16 over four cluster plates). Clusters were fastened securely to both legs at the antero-lateral aspect of the thigh and shank. According to Manal, McClay, Stanhope, Richards, and Galinat (2000), rather than using individual skin markers, using rigid clusters produces the optimal configuration. Figure 3:4 depicts both static and tracking markers.

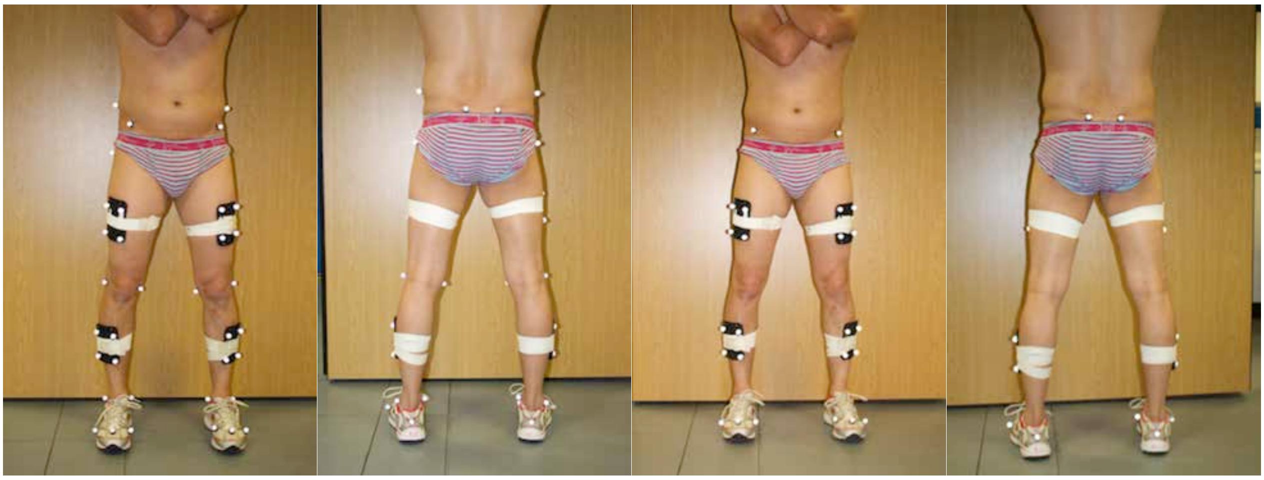

Figure 3:4 Static (left) and tracking (right) marker sets

3.1.2.4.1.2.3 Conducting the tests

To control the interface of the shoe with the surface, prior to testing all participants wore compression shorts and standard shoes (New Balance, UK). To start, participants undertook a 3-min warm up of low-intensity exercise on a cycle ergometer. They then practised each of the two tasks required of them until they were comfortable and familiar with what was required by the testing procedure; on average, this took each participant 2 or 3 goes. Then the principle researcher applied 40 markers to the lower limb of the participant, as described above. Participants were asked to stand stationary on the force plate for the purpose of conducting a static standing trial. To prevent the markers from being detected, the participants were asked to hold their arms clear of the markers by crossing them over chest. Then the anatomical markers were removed and the participant undertook the required SLS then SLL tasks.

- **Single-Leg Squat**

Following the procedure of Herrington (2014), participants were requested to face the video camera, stand on their right leg, and squat as far down as they could manage (between 60° and 80°) for five seconds. In order to limit the influence of knee velocity and standardise the trial for each participant, a count was provided during this period: movement was initiated on the first count, the lowest squat point achieved on the third count, and the full movement completed on the fifth count. Five trials of were performed by each participant. Each trial was considered valid only if the participant achieved the minimum required angle of knee flexion and remained balanced for the duration. During all trials, including practice runs, the same auditor measured the angle of knee-flexion using a standard goniometer.

- **Single-Leg Landing**

Following the procedure of Munro, Herrington, and Carolan (2012), participants were requested to adopt a unilateral posture on the contralateral leg and step forward over a 28cm step, leaning forward and descending vertically to the maximum possible distance, permitting only the landing leg to contact the floor; the contralateral leg was not to make contact with any surface. Five such trials were conducted for each participant.

3.1.2.4.1.2.4 3D Data processing

To calculate the joint kinematic and kinetic data, visual 3D motion (Version 4.21, C-Motion Inc. USA) was used. A Butterworth 4th-order bi-directional, low-pass filter with cut-off frequencies at 12Hz and 25Hz, were used to filter Motion and force-plate data, respectively; the cut-off frequencies were determined according to a residual analysis (Yu, Gabriel, Noble, & An, 1999). inertial parameters were estimated based upon anthropometric data and all lower-extremity segments were then modelled as conical frusta (Dempster, Gabel, & Felts, 1959). An X-Y-Z Euler rotation sequence was used to calculate the angles of the joints, in which X was equal to flexion-extension, Y equal to abduction-adduction/varus-valgus and Z was equal to the internal-external rotation. 3D inverse dynamics were employed to calculate the joint kinetic data. Joint-moment data were normalised to body mass and presented as external moments, which were referenced to the proximal segment. This study describes external moments, e.g. an external knee-valgus load results in a knee abduction (valgus position) and an external knee-flexion load typically flexes the knee (Malfait et al., 2014).

To define the six degrees of freedom movement for each segment, the calibration anatomical systems technique (CAST) was used during the dynamic tasks (Cappozzo, Catani, Leardini, Benedetti, & Croce, 1996). Prior to extracting the data for post-processing using the Qualisys software, a static trial in which the participant was instructed to stand on the force plates with all anatomical and tracking markers visible to the cameras. Bone movement was identified by the reference points offered by the positions of the anatomical markers, through only the tracking markers set during the movement trials.

As Figure 3:5 indicates, there were seven rigid segments attached to the joint that the model used. For each segment, six variables are attributed, which describe the segment's position in 3D space (three of these describe the rotation and the other three variables describe the position of the origin). In particular, three variables describe the rotation about each axis of the segment (sagittal, frontal and transverse) whilst the other three describe the segment translation along three perpendicular axes (vertical, medial-lateral and anterior-posterior). To perform kinetic calculations, the participant's height (in metres) and body mass (in kilograms) were recorded in the software program. To determine the proximal and distal joint/radius, each segment of the pelvis, thigh, shank and foot was modelled.

Furthermore, the hip-joint centre was automatically calculated using ASIS and PSIS markers in the regression equation as defined by Bell, Brand, and Pedersen (1989).

During the SLL task, the event began at IC until the right knee flexion reached 15°ascend; this was chosen to ensure that maximum knee flexion was included in the SLL cycle. During SLS, the point at which the right knee exceeded 15° of flexion was determined to be the commencement of the start phase of the SLS task, which ended when the knee returned to this point while ascending after the task.

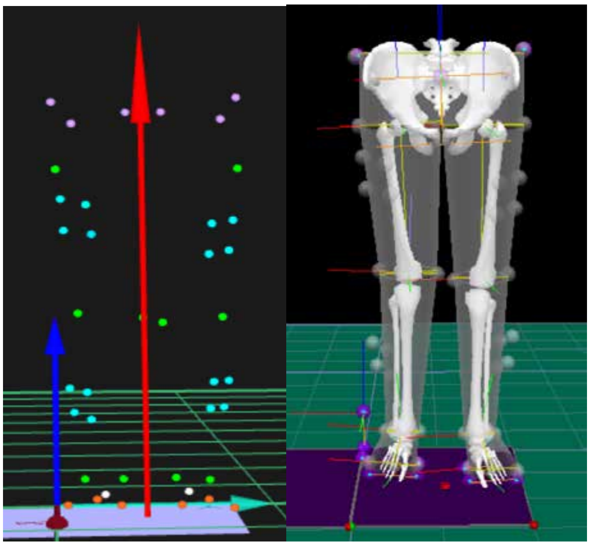

Figure 3:5 QTMTM static models (left), and Visual 3DTM bone model (right)

3.1.2.5 Statistical testing

The validity were assessed using the Pearson's correlation coefficient (r) with the scale as shown in Table 3:2 (Evans, 1996).

Correlation coefficient score	Level of association
0.00-.19	Very weak
0.20-.39	Weak
0.40-.59	Moderate
0.60-.79	Strong
0.80-1.0	Very strong

Table 3:2 Correlation coefficient scores and levels of association (Evans, 1996)

3.1.2.6 Results

Variable	Mean	Std. Deviation
2D SLS FPPA	-9.0273	10.45248
2D SLS Hip Add	70.5760	8.67076
2D SLL FPPA	-10.8887	6.35538
2D SLL Hip Add	79.0467	5.21654
3D SLS Hip Abd Angle	15.1411	6.32281
3D SLL Hip Abd Angle	8.0530	5.66402
3D SLS Knee Abd Angle	-5.6177	5.23224
3D SLL Knee Abd Angle	-7.5190	5.14450

* Negative value means valgus angle.

Table 3:3 Descriptive data for 2D and 3D variables

2D FPPA measurements were found to have strong correlation with knee abduction angle in 3D ($r = 0.66$, $p < 0.008$) during SLS, but not in SLL ($r = 0.075$, $p < 0.79$). Also, 2D FPPA found to be correlated with knee abduction moment ($r = 0.65$, $p < 0.009$) during SLS. 2D FPPA and 2D HADD were found to have strong correlation during SLS ($r = 0.61$, $p < 0.015$), and SLL ($r = 0.53$, $p < 0.044$). 2D HADD showed very strong correlation with 3D HADD during SLS ($r = 0.81$, $p < 0.001$), and strong correlation during SLL ($r = 0.62$, $p < 0.013$). More interestingly, 2D HADD and 3D hip flexion reported strong correlation during SLS ($r = 0.60$, $p < 0.018$).

3.1.2.7 Conclusion

2D measurements during single leg squat and single leg landing have strong criterion validity in some measurements of lower limb kinematics compared with the 3D method.

3.1.3 Two-dimensional (2D) Video Reliability

3.1.3.1 Background

The three-dimensional (3D) system has been used extensively to study knee injury risk factors; it is used as a gold standard to measure the lower limbs kinetics and kinematics. There are some disadvantages in using 3D system such as the cost of the system, the cost of use, the length time needed for data collection and analysis, the need for a trained individual to use the system, and the inability to use it outdoors or to transfer it to a data collection site where it is difficult to bring some subjects to the system location. These disadvantages make the system inappropriate, especially with large screening projects.

Some previous studies have investigated the reliability of 2D screening in some specific tasks as explained previously (section 2.4.2)

3.1.3.2 Purpose

The goal of this study was to determine the reliability of the two-dimensional (2D) procedure to measure the frontal plane kinematics during a single leg squat (SLS) and single leg landing (SLL). Moreover, the intra- and inter-rater reliability, standard error of measurement (SEM), and small detectable difference (SDD) were established.

3.1.3.3 Method

The same method and procedure as for the validity study were used. Intraclass correlation coefficients (ICCs) were calculated to determine the reliability of 2D within sessions and between sessions, and the standard error of measurement (SEM) was used to establish measurement error. Intra-rater and inter-rater reliability were calculated for both tasks among all participants. The small detectable difference (SDD) was established. The levels of ICC were interpreted according to the criteria shown in Table 3:4 (Coppieters, Stappaerts, Janssens, & Jull, 2002).

ICC Value	Interpretation
$ICC < 0.40$	Poor
$0.40 \leq ICC < 0.70$	Fair
$0.70 \leq ICC < 0.90$	Good
$ICC \geq 0.90$	Excellent

Table 3:4 ICC values and corresponding levels

3.1.3.4 Results

Each subject was tested for each task (SLS and SLL) over three different sessions. The first and second sessions were on the same day (within-session); the third session was one week later (between-session). Intraclass correlation coefficients (ICCs) were calculated to determine within-session and between-sessions reliability.

- **2D reliability within-session**

In SLS, 2D FPPA measurements demonstrated good within-session reliability (ICC = 0.72, 95% CI = 0.086–0.915). 2D HADD also demonstrated good within-session reliability (ICC = 0.911, 95% CI = 0.710–0.973). For SLL, within-session reliabilities were (ICC = 0.871, 95% CI = 0.576–0.961) and (ICC = 0.893, 95% CI = 0.649–0.967) for FPPA and HADD respectively.

- **2D reliability between-session**

In SLS, 2D FPPA measurements showed good between-session reliability (ICC = 0.869, 95% CI = 0.569–0.960). 2D HADD also demonstrated good between-session reliability (ICC = 0.792, 95% CI = 0.319 - 0.937). For SLL, between-session reliabilities were (ICC = 0.872, 95% CI = 0.581–0.961) and (ICC = 0.859, 95% CI = 0.538–0.957) for FPPA and HADD respectively.

SLS				SLL			
Within-session reliability		Between-session reliability		Within-session reliability		Between-session reliability	
FPPA	HADD	FPPA	HADD	FPPA	HADD	FPPA	HADD
ICC = 0.72	**ICC = 0.911**	**ICC = 0.869**	**ICC = 0.792**	**ICC = 0.871**	**ICC = 0.893**	**ICC = 0.872**	**ICC = 0.859**
95% CI = 0.086 to 0.915	95% CI = 0.710 to 0.973	95% CI = 0.569 to 0.960	95% CI = 0.319 to 0.937	95% CI = 0.576 to 0.961	95% CI = 0.649 to 0.967	95% CI = 0.581 to 0.961	95% CI = 0.538 to 0.957

Table 3:5 2D reliability results; within-session and between session

- **Intra-reliability**

Intra-reliability for the first tester was calculated in SLS and SLL. This tester had to analyse the 2D videos of all subjects for a second time to measure FPPA and HADD. The correlation was found to be very large between the two measurements for both variables in both tasks. In SLS, FPPA and HADD reported correlations were (ICC = 0.991) and (ICC = 0.987) respectively. In SLL, FPPA and HADD correlations were (ICC = 0.990) and (ICC = 0.967) respectively.

- **Inter-reliability**

Inter-reliability between two testers was assessed in both tasks. The second tester was asked to analyse 2D videos of all subjects to measure FPPA and HADD. In SLS, the correlation was found to be very large for both variables. FPPA and HADD reported correlations were (ICC = 0.974) and (ICC = 0.962) respectively. In SLL, FPPA and HADD were found to be very correlated, with (ICC = 0.988) and (ICC = 0.985) respectively.

SLS				SLL			
Intra-reliability		Inter-reliability		Intra-reliability		Inter-reliability	
FPPA	HADD	FPPA	HADD	FPPA	HADD	FPPA	HADD
0.991	0.987	0.974	0.962	0.990	0.967	0.988	0.985

Table 3:6 2D Inter- and intra-reliability “ICC” results

- **Standard Error of Measurement (SEM):**

The standard error of measurement was calculated for all variables using the formula SEM = SD (pooled) x (√1-ICC) (Thomas, Nelson, & Silverman, 2005). The SEM for this study was very low, which gives more confidence to the findings of the results using the 2D tool.

SLS				SLL			
Within-session		Between-sessions		Within-session		Between-sessions	
FPPA	HADD	FPPA	HADD	FPPA	HADD	FPPA	HADD
1.41°	0.37°	0.69°	0.93°	0.43°	0.32°	0.40°	0.43°

Table 3:7 2D Standard Error of Measurement

- **Small Detectable Difference (SDD):**

According to Denegar and Ball (1993), genuine changes can be distinguished from erroneous measurements by using the standard error of measurement. Nevertheless, Atkinson and Nevill (1998) and Thomas et al. (2005) noted that as little as 68% of all test scores come within one SEM of the correct score, in contrast to the frequently employed benchmark of 95%.Therefore, the SDD statistic has been used to determine the amount of change needed to signify statistical significance (Atkinson & Nevill, 1998; Eliasziw, Young, Woodbury, & Fryday-Field, 1994). It has been known as the minimum value that should be exceeded to distinguish between random errors in measurement and a real change in performance score (Atkinson & Nevill, 1998; Eliasziw et al., 1994). Hence, in the present work, the SDD was calculated according to the formula cited by Kropmans, Dijkstra, Stegenga, Stewart, and de Bont (1999): SDD = $1.96 * (\sqrt{2}) * SEM$.

Eliasziw et al. (1994) argue that, as the product of the standard normal distribution and the SEM, the SDD provides improved accuracy over the 95% confidence benchmark of the SEM, with a difference between two measurements that is larger than the SDD being regarded as statistically significant. This provides clinicians with enhanced understanding in the assessment of changes observed during intervention, rehabilitation or training.

SLS				**SLL**			
Within-session		Between-sessions		Within-session		Between-sessions	
FPPA	HADD	FPPA	HADD	FPPA	HADD	FPPA	HADD
3.91°	1.03°	1.91°	2.58°	1.19°	0.89°	1.11°	1.19°

Table 3:8 Small Detectable Differences

3.1.3.5 Conclusion

2D is found to be a reliable method of testing the lower limb kinematics within and between sessions. Also, it has good intra- and inter-reliability with low standard error of measurements and small detectable difference values.

3.2 The 2D Validity and Reliability Discussion

The present study showed that SLS and SLL tasks are reliable within days and between days. This supports the work of Munro, Herrington, and Carolan (2012) for both tasks and Gwynne and Curran (2014) for SLS. The within-day reliability in the present study for FPPA in SLS was 0.72, whereas it was 0.59–0.86 in the study by Munro, Herrington, and Carolan (2012) and 0.86 for Gwynne and Curran (2014). The between-day reliability in the present study for FPPA in SLS was 0.87, whereas it was 0.72–0.82 for Munro, Herrington, and Carolan (2012) and 0.74 for Gwynne and Curran (2014). However, the within-reliability in the present study of FPPA in SLL was 0.87 compared with 0.75–0.79 in Munro, Herrington, and Carolan (2012) and the between-day reliability was 0.87 compared with 0.8–0.82 for Munro, Herrington, and Carolan (2012). The present study showed that between-days reliability was slightly higher than the within-days reliability. The reason for this was not clear. However, it can be partially explained by the larger confidence intervals for within day, although there was no significant difference in mean scores. Generally, the SEM in the current study (see Table 3:7) was less than those reported by Munro, Herrington, and Carolan (2012), which ranged between 2.72° and 3°, and by Gwynne and Curran (2014), whose SEM ranged between 2° and 3.8° in both tasks.

No studies have investigated the SLS and SLL intra and inter-reliability, and no work has been done to examine the hip adduction angle reliability. Therefore, reporting these results was one of the main contributions of this study. However, a recent study by Tate, True, Dale, and Baker (2015) was published after the present study was finished, showing the inter- and intra-reliability of FPPA during SLS ranging between 0.91 and 0.96, which was a similar range to that of the present study (0.97–0.99). Another recent study by Ugalde, Brockman, Bailowitz, and Pollard (2015) reported a smaller inter-reliability ranging between 0.45 and 0.72. The smaller inter-reliability might be due to the inclusion of certified athletic trainers rather than a physiotherapist, so the level of training and experience might have influenced the result. The findings of the present paper along with those of Gwynne and Curran (2014) and Munro, Herrington, and Carolan (2012) indicate that the methods used are sufficiently robust to provide reliable results across multiple testers and time points, which opens up the possibility of using these tests in multi-centre trials.

Regarding the validity, only a few studies have investigated the association between 2D and 3D knee and hip motion during functional tasks (Gwynne & Curran, 2014; McLean, Huang, & van den Bogert, 2005; Sorenson et al., 2015; Willson & Davis, 2008). When assessing similar tasks, Willson and Davis (2008) found a moderate relationship during SLS of FPPA to knee abduction angle assessed with the 3D system ($r = 0.48$), which was smaller than the present study finding ($r = 0.66$, $p < 0.008$). Also, Gwynne and Curran (2014) found a strong relationship between FPPA and 3D knee abduction angle ($r = 0.78$) during SLS which is stronger than the present study finding. However, the present study found no correlation between SLL FPPA and 3D knee valgus whereas a study by Sorenson et al. (2015) found that FPPA had a strong relationship to 3D knee abduction angle ($r = 0.72$) during single leg drop jump at initial contact, which is the opposite of the present study finding ($r = 0.075$, $p < 0.79$).

When the findings from the literature are considered with ours, it would appear that both FPPA and HADD measured using 2D video have a strong relationship with comparable measurements using 3D motion capture, especially for less complex and dynamic tasks such as SLS. The difference in validity between the two tasks (SLS and SLL) might be due to the difference between the tasks and their impact on matching the exact moment of maximum knee flexion angle. FPPA was captured at the point of maximum flexion; however, because of the different capture speeds of the two systems, during the high-speed task of SLL, the poor correlation could relate to an inability to measure at exactly the same knee flexion point. During the slower task of SLS, it is more likely that the two systems coalesce.

The present study has some limitations as with other 3D motion capture studies using external marker sets, as the skin-movement artefact has the potential to influence the data. Different markers were used for measurement for the two systems, which again could have led to systematic error. Future research should perhaps consider using the same markers and taking care to measure at the same points. Further research is needed to identify whether these findings extend to analyses performed using clinical techniques, as well as during other activities such as bilateral leg landings, cutting activities, and other dynamic tasks. Moreover, the inter-rater reliability in this study assessed only the agreement between the two assessors in extracting the relevant angles from the 2D videos. The potential sources of inter-rater error could be: (1) placement of the markers; (2) digitisation of the markers; (3) measurement of the angles. The inter-tester reliability in this study tested only the last two sources; it did not assess the first source.

The present study adds to the growing body of evidence suggesting that 2D video analysis of a variety of single leg tasks has a reasonable association to what is being measured using 3D motion capture. The findings of this study also show that the approach has good reliability, within and between sessions and also between examiners.

Chapter (4)

Performance of Biomechanical

Tasks Across a Season

Chapter 4: Performance of Biomechanical Tasks Across a Season

4.1 Introduction

Assessment of functional athletic tasks has become increasingly used in recent years to predict knee injuries and to provide an outcome measure for evaluating athletes who are returning from injury (Delextrat & Cohen, 2008; Hewett et al., 2005; Munro, Herrington, & Carolan, 2012). These functional tasks have been studied and found to be valid and reliable in measuring the lower limb kinematics as discussed in the method chapter (Willson & Davis, 2008). Although many studies have examined the relationship of the performance of these tasks to lower limb injuries, there have been no studies to investigate the performance change across time and its relation to injury, and the factors related to performance change. Also, the performance difference between dominant and non-dominant legs has not been studied. That being the case, it is very important to investigate the task performance over time to see where this could be linked to the different rate of lower limb injuries that occur at different times during the sports season, assuming that there is a link between performance and injury. A few studies have reported the incidence rate of sports injuries across the season, and have reported different incidence rate for injuries across the season, and across match and training time. In a four-year study of ACL injury incidence, Dodson et al. (2016) reported the highest rate of injuries during the pre-season practice and games. In another four-year study, Bradley et al. (2002) reported the same pattern of highest ACL injuries during the pre-season practice and games. Even though these studies included both contact and non-contact ACL injuries, it remains important to study the performance change over time and its relation to injuries and how that could contribute to injury prevention programmes, and to determine whether the relative risk of injury depends on changes in performance over time.

4.2 Methods

4.2.1 Participants

All participants in the study are male football players aged 16-30 years old. Data were collected during some of the typical athletic tasks described in section 4.2.5. The inclusion criteria outlined in the next part refer to the form in Appendix 1.

4.2.2 Sample size

Louw et al. (2008) conducted a systematic review that reported that prevalence of knee injuries was 10–25% of sports injuries in active adolescents. It is impossible to use the formal sample size calculation due to the lack of information in the prospective studies of knee injuries risk factors. None of the studies used in the systematic review were prospective studies. Moreover, a limited number of prospective studies of knee injuries incidence have been conducted using sample sizes varying from 268 to 890 subjects per season (Gomez, DeLee, & Farney, 1996; Junge, Cheung, Edwards, & Dvorak, 2004; Junge, Chomiak, & Dvorak, 2000; Messina, Farney, & DeLee, 1999; Pasque & Hewett, 2000). Therefore, 200 subjects might report at least 20–50 knee injuries during one sports season, which might fulfil these study objectives. However, it proved impossible to recruit such a large number of subjects, for reasons that will be mentioned in the discussion (section 4.4).

4.2.3 Inclusion/Exclusion Criteria:

1. Male aged 16–30 years old.

2. Football player (participates in professional sports team).

3. Has not had a significant injury in the lower limbs in the previous six months. 'Significant injury' is defined as an injury that prevented him from attending five consecutive training sessions.

4. Is able to do single leg squat and single leg landing tasks independently without aids.

5. The form in Appendix 4 is to assess the general health of participants. If any participant answers yes to any of the questions, they were asked to provide a letter from their GP before being allowed to participate in this study.

The form in Appendix 1 is to assess the participant's history of injuries. If any participant answers yes to the question 'Has this injury prevented you from attending five consecutive training sessions?', he was excluded.

4.2.4 Screening tools

2D and 3D are the standard tools that have been used to identify people at higher risk of knee injuries in the literature. Each tool has advantages and disadvantages. The 3D system has been used as the gold standard in identifying athletes at higher risk of injury (Munro, Herrington, & Carolan, 2012).

The 3D system has some disadvantages that made it inappropriate for use in this study. The between-sessions reliability of the 3D system in prospective studies is still questioned due to the error sensitivity in marker placement and skin movement (Cappozzo, Catani, Leardini, Benedetti, & DellaCroce, 1996; Ford et al., 2007). Another important reason for not using the 3D system is the time needed for data collection and analysis for this large screening study. These disadvantages have created a gap between research and clinical practice because assessing the players usually happens in the sports clubs and clinics where a simpler and easier tool such as the 2D system is required. Therefore, investigating the capability of the 2D technique to identify athletes who are at higher rate of injury will make this simpler tool more usable at sports clubs and clinics. Moreover, specifically for this large screening study, bringing subjects to the 3D facility lab is impractical due to the large number of participants and the number of test sessions.

2D is the other tool that has been used to identify people at higher risk of knee injuries. The frontal plane projection angle (FPPA) has been used for this purpose (McLean, Walker, et al., 2005; Mizner et al., 2012; Willson & Davis, 2008). The validity of the FPPA method in relation to 3D has been investigated during some sports functional tasks (McLean, Walker, et al., 2005; Willson & Davis, 2008). FPPA was found to be significantly correlated ($r = 0.72$) with the knee valgus angle in 3D during single leg drop jump landing at initial contact, which might represent the SLL (Sorenson et al., 2015). Moreover, McLean, Walker, et al. (2005) found that FPPA was significantly correlated with peak 3D knee valgus angles ($r = 0.58$–0.64) during side step and side jump. Willson and Davis (2008) found that 2D FPPA was significantly correlated with 3D hip adduction ($r = 0.32$) and knee external rotation angles ($r = 0.48$) during SLS. Additionally, Herrington, Alenezi, Alzhrani, Alrayani, and Jones (2017) found that 2D FPPA has a large correlation with knee abduction angle in 3D ($r = 0.66$) during single leg squatting. In conclusion, 2D FPPA may be useful to identify athletes at high risk of knee injuries (See chapter 3 for the validity and reliability study).

The reliability of the 2D method was investigated within and between sessions. Herrington et al. (2017) found a strong reliability within and between sessions during single leg squatting (SLS) and single leg landing (SLL). They also reported large intra-rater and inter-rater reliability; and very low SEM. Moreover, Willson et al. (2006) reported good within-session reliability of 2D FPPA.

All data was collected using two digital cameras (2D analysis), which were provided by the School of Health and Sciences at the University of Salford. Other tools used in the study include a 28-cm step and collaboration triangle.

4.2.5 Athletic tasks

- **Single-Leg Squat**

Subjects were asked to stand on one leg, facing the video camera. They were asked to squat down as far as possible, to at least 60° but no greater than 80°, for five seconds, for five trials. The knee flexion angle was checked during practice trials using a standard goniometer, and then observed by the same examiner throughout the trials. There was also a counter for each participant over this five-second period, in which the first count initiates the movement, the third indicates the lowest point of the squat, and the fifth indicates the end. This standardised the test for all participants, thereby reducing the effect of velocity on knee angles. Trials were only accepted if the subject squatted to the minimum desired degree of knee flexion and maintained balance throughout (Herrington, 2014). Both legs performed same task.

- **Single-Leg Landing**

Subjects dropped from a 28-cm step, again leaning forward and dropping as far vertically as possible. They were asked to take a unilateral stance on the contralateral limb and to step forward to drop onto the floor corresponding to the landing leg, ensuring that the contralateral leg makes no contact with any other surface, for five trials (Munro, Herrington, & Carolan, 2012). Both legs were tested.

4.2.6 Study Procedure

For each subject, hip angle and knee frontal plane projection angle (FPPA) data was recorded for the right and left leg during the execution of SLS and SLL. Subjects were asked to perform five successful trials for each task and for each leg, and a successful trial required the movement to occur in the field of the 2D camera. The videotaping recorded the subject trunk and lower limbs only. A commercially available digital video camera (Sony Handycam DCR- HC37, Sony Corp, Tokyo, Japan) sampling at 30 fps was used. The camera was placed at the height of 60 cm from the floor, 2 m anterior to the subject's landing target, and was aligned perpendicular to the frontal plane (Herrington & Munro, 2010). Markers were placed at the midpoint of the ankle malleoli for the centre of the ankle joint, the midpoint of the femoral condyles to approximate the centre of the knee joint, and on the both anterior superior iliac spines (ASIS) (Willson et al., 2006). FPPA of the knee and hip angle were measured using Quintic Biomechanics software (version 26). FPPA was defined as the angle subtended between the line from the markers on the ASIS to the knee joint and the line from the knee joint to the ankle. The hip angle was defined as the angle between the line from the marker on the ASIS to the knee joint and the line connecting both ASISs. Both FPPA and hip angle were measured at the frame, which represents the point of maximum knee flexion. This was determined as the lowest point of the squat and landing tasks.

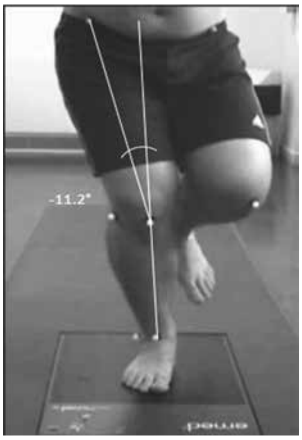

Figure 4:1 A Frontal view of the procedure set up as in (*adapted from Gwynne and Curran, 2014*

The data was collected as explained previously (pre-season, start-season, and end-season) during the football season of 2015–16. All data collected in all three sessions was compared and studied among all participants. Data of players who suffered injuries during the season was collected and are presented in chapter 6. All the testing and data collection have been done in the location of the participating teams. The full procedure including data collection and angle calculation from the videos have been done by a physiotherapist "author of this thesis" who has a 9 years of experience in sport physiotherapy. The injuries data was collected from the team's records for the full season.

Pre-season collection	July, 2015
Start-season collection	August 'week 1-4'; 2015
End-season collection	April 'week 36-40'; 2016

Table 4:1 Data collection timing

4.2.7 Participants table

Four professional football clubs were involved in this study from the northwest of England. A total of 124 footballers consented to take part but only 90 met the inclusion criteria. The players' average age was 18.8±4 years, height 179.2±6 cm and weight 73.3±6 kg. 14 players are left leg dominant; the others are right leg dominant.

	Team1	Team2	Team3	Team4	Total
Consent to participate	29	28	29	38	**124**
Met the Criteria	19	17	20	34	**90**
Pre-season	19	17	20	34	**90**
Start-season	18	16	17	27	**78**
End-season	19	17	16	18	**70**

Table 4:2 Table of participants

4.2.8 Statistical analysis

All statistical tests were conducted using IBM SPSS Statistics software version 23. Two-way repeated measures ANOVA were run to examine the task performance interaction between time and limb using the FPPA and hip angles as outcome measures for each task (SLS, SLL). For both outcome variables, analysis of the studentised residuals showed that all variables met the normality assumption, as assessed by the Shapiro–Wilk test and no outliers, as assessed by no studentised residuals greater than ± 3 standard deviations. The sphericity for the interaction term was assessed by Mauchly's test of sphericity. If $p > 0.05$, it meets the assumption of sphericity. If $p < 0.05$, it violates the assumption of sphericity and an epsilon (ε) correction method (Greenhouse–Geisser or Huynh–Feldt) was used to report the test result; the value closer to 1 was used because it means less violation.

If the two-way repeated measures ANOVA were statistically significant in (time*limb) interaction, one-way repeated measure ANOVA was used to compare the difference over time, and t-tests were used to compare differences between limbs (dominant, non-dominant); and between any two screening sessions (pre-season, start-season, end-season). In contrast, if the two-way repeated measures ANOVA showed no statistical significance in (time*limb) interaction, the main simple effect for each factor alone (limb, time) can be used to examine the difference significance overall for each factor. Then, t-tests were used to compare differences between limbs (dominant, non-dominant); and between any two screening sessions (pre-season, start-season, end-season) if the factor of overall differences was statistically significant.

4.3 Results

4.3.1 Performance descriptive statistics

The descriptive statistics show the means and standard deviations for FPPA and hip angles for both legs in both tasks, for each screening session. It is important to mention that the negative mean indicates the valgus angle and the positive mean indicates the varus angle. Also, a lower hip angle means greater hip adduction. The players with missing data (due to error or absence) at each screening session were excluded and the new number of participants was reported.

4.3.2 Pre-season performance

SLS

Dominant FPPA (n = 88) averaged -4.35°±9.48 whereas non-dominant FPPA averaged -0.64°±8.28. Also, the dominant hip angle (n = 88) averaged 73.15°±8.95, whereas the non-dominant hip angle averaged 74.53°±8.13.

SLL

Dominant FPPA (n = 88) averaged -5.02°±7.89, whereas the non-dominant FPPA averaged -2.30°±7.82. Also, the dominant hip angle (n = 88) averaged 80.91°±6.20, whereas the non-dominant hip angle averaged 81.58°±5.99. Figure 4:2 shows the pre-season performance for both tasks in both legs.

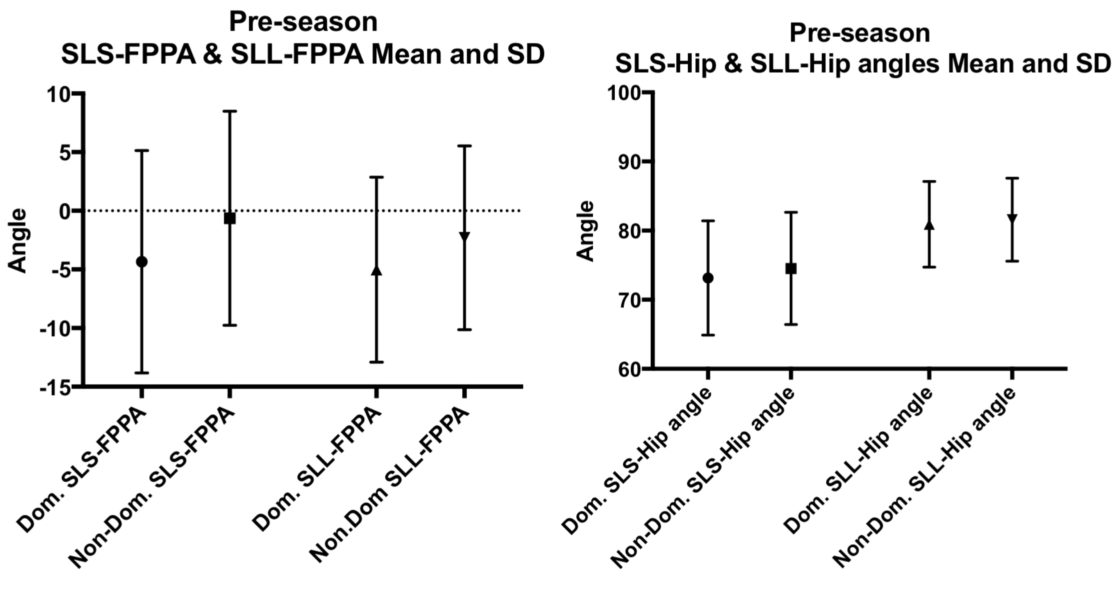

Figure 4:2 Pre-season performances for FPPA & Hip angle

4.3.3 Start-season performance

SLS

Dominant FPPA (n = 77) averaged -4.30°±9.47, whereas the non-dominant FPPA averaged -0.78°±7.77. Also, the dominant hip angle (n = 77) averaged 73.33°±8.06, whereas the non-dominant hip angle averaged 75.85°±7.10.

SLL

Dominant FPPA (n = 75) averaged -2.82°±8.69, whereas the non-dominant FPPA averaged 0.04°±7.65. Also, the dominant hip angle (n = 75) averaged 82.19°±6.30, whereas the non-dominant hip angle averaged 83.72°±5.11. Figure 4:3 shows the start-season performance for both tasks in both legs.

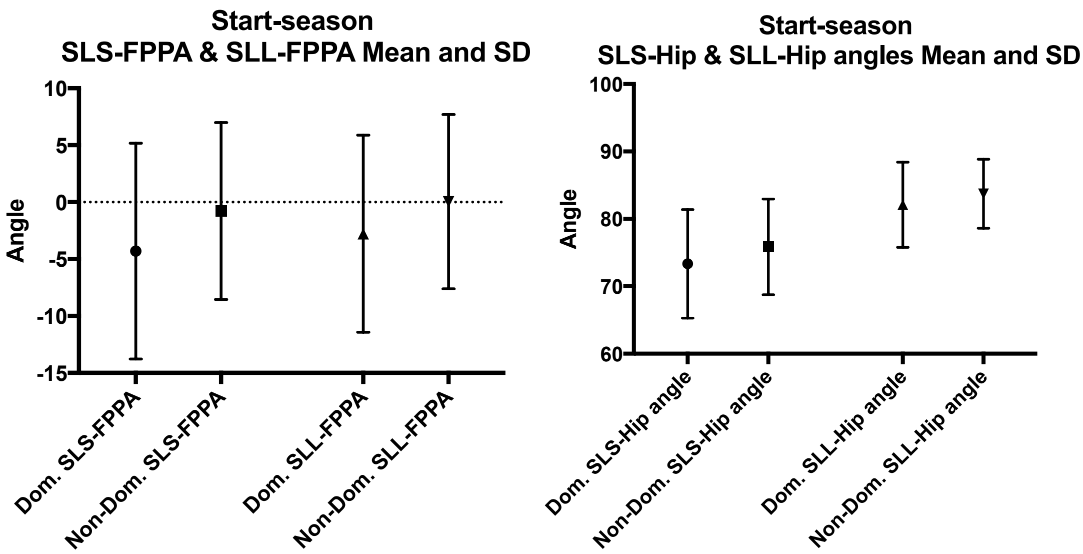

Figure 4:3 Start-season performances for FPPA & Hip angle

4.3.4 End-season performance

SLS

Dominant FPPA (n = 67) averaged -2.84°±7.71, whereas the non-dominant FPPA averaged -1.25°±8.40. Also, the dominant hip angle (n = 67) averaged 73.47°±7.93, whereas the non-dominant hip angle averaged 74.94°±6.98.

SLL

Dominant FPPA (n = 65) averaged -1.69°±8.52, whereas the non-dominant FPPA averaged 2.54°±8.15. Also, the dominant hip angle (n = 65) averaged 83.55°±5.03, whereas the non-dominant hip angle averaged 85.39°±5.55. Figure 4:4 shows the end-season performance for both tasks in both legs.

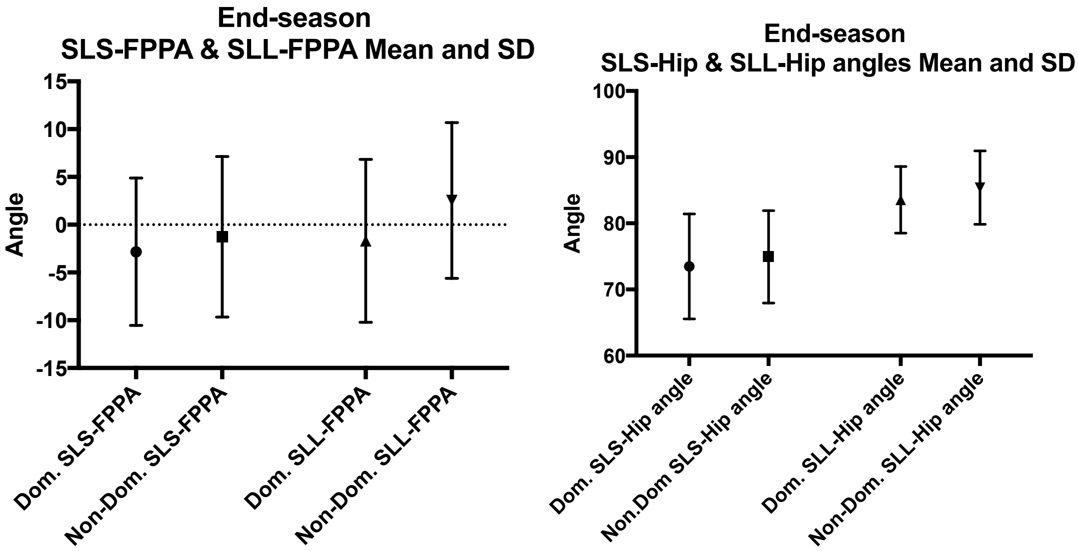

Figure 4:4 End-season performances for FPPA & Hip angle

Statistical testing:

The two-way repeated measures ANOVA revealed no statistically significant interaction between limb and time in both SLS-FPPA and SLS-hip angle performance: F (2, 124) = 1.86, $p < 0.16$ and F (2, 124) = 0.17, $p < 0.85$, respectively. However, the main simple effect in SLS-FPPA was statistically significant in limb, F (1, 62) = 8.07, $p < 0.006$ but not in time F (2, 124) = 0.91, $p < 0.40$, whereas the main simple effect for limb and time in SLS-hip angle performance was statistically significant, F (1, 62) = 5.11, $p < 0.027$ and F (2, 124) = 3.43, $p < 0.035$ respectively.

Also, the two-way repeated measures ANOVA revealed no statistically significant interaction between limb and time in both SLL-FPPA and SLL-hip angle performance: F (2, 118) = 2.59, $p < 0.079$ and F (2, 118) = 1.37, $p < .257$, respectively. However, the main simple effect in SLL-FPPA was statistically significant in time, F (2, 118) = 16.30, $p < 0.0005$ but not in limb F (1, 59) = 3.76, $p < 0.057$. Also, the main simple effect in SLL-hip was statistically significant in time, F (2, 118) = 17.93, $p < 0.0005$ but not in limb F (1, 59) = 1.51, $p < 0.224$.

4.3.5 Effect of Limb

The two-way repeated measures ANOVA found no statistically significant interaction between time and limb in SLS-FPPA, SLL-FPPA, SLS-hip and SLL-hip angles performance, but the simple main effect for leg was statistically significant in SLS-FPPA and SLS-hip angles. Therefore, multiple paired t-tests were run to investigate the performance differences between limbs (dominant, non-dominant) for SLS-FPPA and SLS-hip in each screening session. The alpha level of (α = 0.05) was adjusted to (α = 0.05/3 = 0.017) for multiple comparisons. Also, multiple paired t-tests were run to investigate the performance differences between limbs for SLL-FPPA and SLL-hip even where no statistical significant difference was found in the repeated measure test results. This is because the repeated measure test did not include 33% of the players as it includes only the players who have attended all three screening sessions, while we are studying each screening session alone.

Table 4:3 and Table 4:4 show the statistical tests result of difference between legs for FPPA & hip angle for SLS and SLL tasks, respectively, for each screening session.

Screening session	*In SLS*	*Dominant leg M±SD*	*Non-dominant leg M±SD*	*Stat. test*	*Mean Difference ±SD*	*P value*	*Confidence interval*
Pre-season	FPPA	-4.35°±9.48°	-0.64°±9.12°	t(87)= -3.84	-3.71°±9.07	0.0005*	-5.64° to -1.79°
	Hip angle	73.15°±8.28°	74.53°±8.13	t(87)= -1.94	-1.37°±6.64	0.055	-2.78° to 0.03°
Start-season	FPPA	-4.30°±9.47°	-0.78°±7.77	t(76)= -3.10	-3.52°±9.95	0.003*	-5.78° to -1.26°
	Hip angle	73.33°±8.06°	75.85°±7.10°	t(76)= -3.07	-2.52°±7.20	0.003*	-4.15° to -0.89°
End-season	FPPA	-2.84°±7.71°	-1.25°±8.40	t(66)= -1.29	-1.58°±9.99	0.199	-4.01° to 0.85°
	Hip angle	73.47°±7.93°	74.94°±6.98°	t(66)= -1.88	-1.47°±6.40	0.064	-3.03° to 0.09°

Table 4:3 Results of statistical tests of difference between legs for SLS-FPPA & SLS-hip angle

Screening session	*In SLL*	*Dominant leg M±SD*	*Non-dominant leg M±SD*	*Stat. test*	*Mean Difference ±SD*	*P value*	*Confidence interval*
Pre-season	FPPA	-5.02°±7.89	-2.30°±7.82	t(87)= -2.64	-2.72°±9.65	0.010*	-4.76 to -0.67
	Hip angle	80.91°±6.20	81.58°±5.99	t(87)= -0.98	-0.67°±6.46	0.33	-2.04 to 0.70
Start-season	FPPA	-2.82°±8.69	0.04°±7.65	t(74)= -2.72	-2.86°±9.13	0.008*	-4.96 to -0.76
	Hip angle	82.19°±6.30	83.72°±5.12	t(74)= -2.29	-1.53°±5.80	0.025	-2.86 to -0.20
End-season	FPPA	-1.69°±8.52	2.54°±8.16	t(64)= -3.02	-4.23°±11.28	0.004*	-7.02 to -1.43
	Hip angle	83.55°±5.03	85.39°±5.55	t(64)= -2.14	-1.83°±6.93	0.03	-3.55 to -0.11

Table 4:4 Results of statistical tests of difference between legs for SLL-FPPA & SLL-hip angle

In summary, the results show a statistical significant difference between dominant and non-dominant leg FPPA in all the screening sessions for both tasks except at end-season screening for SLS. The dominant leg FPPA was more valgus than the non-dominant leg in all screening sessions for both tasks. However, the results revealed no statistical significant difference between the dominant and non-dominant leg hip adduction angle in all the screening sessions for both tasks except in start-season screening for SLS. The dominant hip was more adducted (had a smaller hip angle) than the non-dominant hip in all the screening sessions for both tasks.

4.3.6 Effect of Time

Prior to reporting the statistical analysis results, Figure 4:5 visualize the descriptive results of dominant leg performance over time (between sessions) for FPPA and hip angle for both tasks (SLS & SLL). Figure 4:6 visualize the descriptive results for non-dominant leg performance.

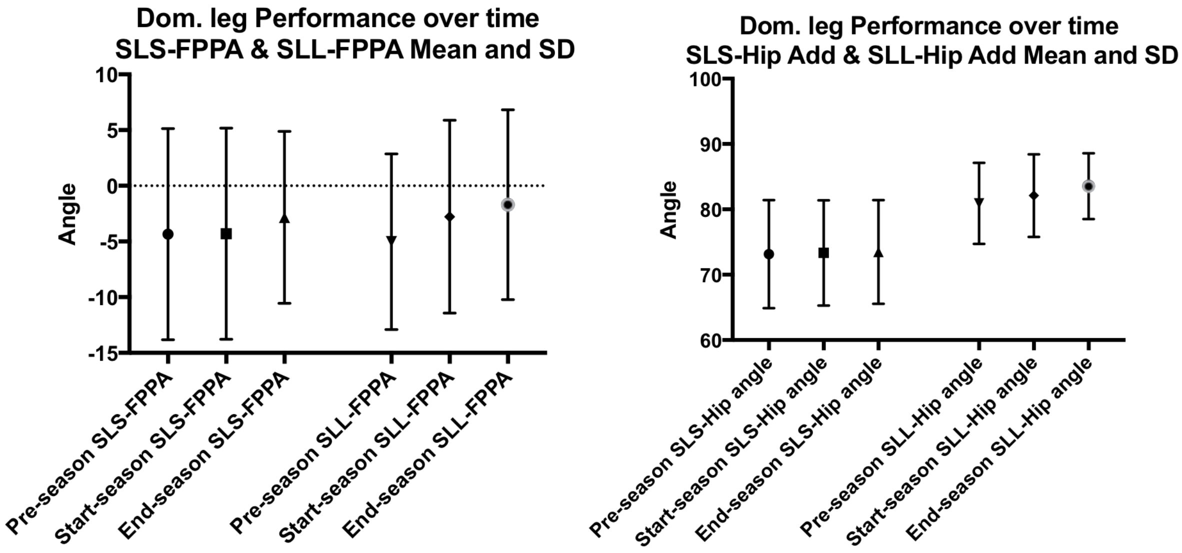

Figure 4:5 Dominant leg performances over time (between sessions) FPPA & hip angle

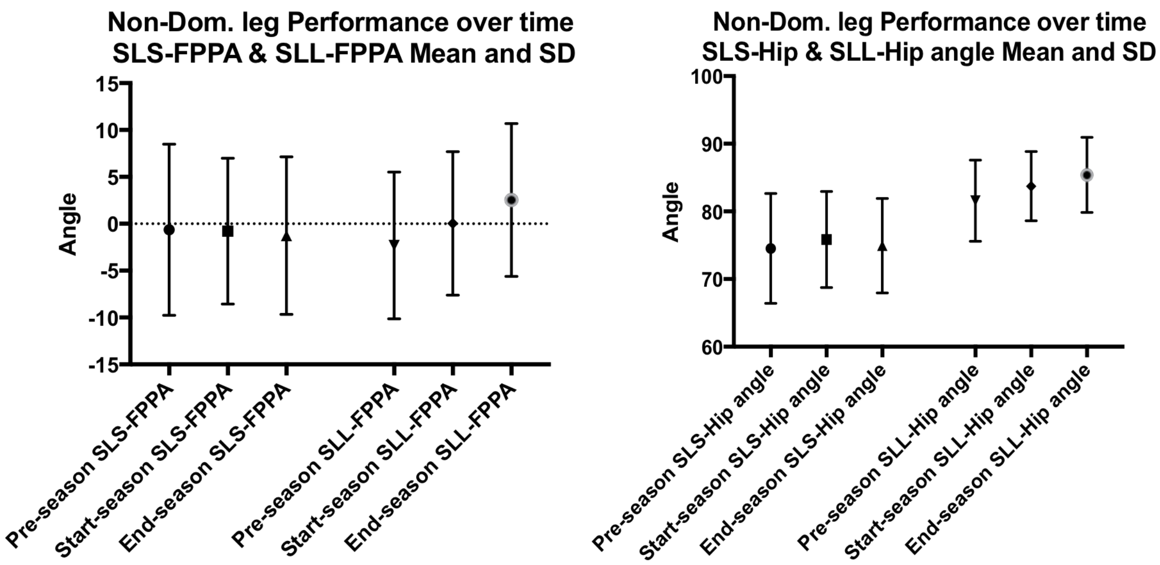

Figure 4:6 Non-dominant leg performances over time (between sessions) FPPA & hip angle

The two-way repeated measures ANOVA found no statistically significant interaction between time and limb in SLS-FPPA, SLL-FPPA, SLS-hip and SLL-hip angles performance, but the simple main effect for time was statistically significant in SLS-hip, SLL-FPPA and SLL-hip angles. Therefore, multiple one-way repeated measure ANOVA was used to investigate the differences over time for each variable alone. A multiple paired t-test was run to investigate the performance differences between every two screening sessions for both legs of SLS-hip, SLL-FPPA and SLL-hip. The alpha level of (α = 0.05) was adjusted to (α = 0.05/3 = 0.017) for multiple comparisons.

Table 4:5 shows the results of one-way repeated measure ANOVA of every variable alone to see which variable has a significant difference over time excluding the SLS-FPPA as the two-way repeated measure showed no significant interaction between time and limb.

Screening	*Variable*	*Leg*	*Pre-season mean*	*Start-season mean*	*End-season mean*	*Stat. Test*	*P value*
SLS	Hip angle	Dom.	72.14°±9.03	73.78°±8.11	73.52°±8.15	F(2,124)= 2.25	0.19
		Non-Dom.	73.63°±9.03	75.67°±7.20	74.93°±7.15	F(2,124)= 2.81	0.06
SLL	FPPA	Dom.	-3.91°±8.11	-1.76°±8.65	-1.49°±8.67	F(2,120)= 4.76	0.010*
		Non-Dom.	-2.43°±8.72	-0.45°±7.58	2.31°±8.35	F(2,118)= 14.63	0.0005*
	Hip angle	Dom.	81.65°±6.14	82.63°±6.10	83.66°±5.08	F(2,120)= 6.03	0.003*
		Non-Dom.	82.03°±6.16	83.52°±5.23	85.37°±5.67	F(2,118)= 14.82	0.0005*

Table 4:5 Results of performance change over time for FPPA & hip angle in both tasks.

The following tables show the performance differences between each two screening sessions (pre-season to start-season, start-season to end-season, and pre-season to end-season).

Pre-season to start-season differences

Table 4:6 shows the results of statistical tests of change of performance between pre-season and start-season.

Screening		*Leg*		*Pre M ±SD*	*Start M ±SD*	*Stat. test*	*Mean difference ±SD*	*P value*	*Confidence interval*
Pre To Start change	*SLS*	Dom.	Hip angle	72.98°±8.60	73.33°±8.06	t(76)= -0.40	-0.35°±7.56	0.68	-2.07 to 1.36
		Non-Dom.	Hip angle	74.38°±8.55	75.85°±7.10	t(76)= -1.78	-1.47°±7.26	0.07	-3.12 to 0.17
	SLL	Dom.	FPPA	-4.78°±8.15	-2.77°±8.65	t(75)= -2.99	-2°±5.86	0.004*	-3.35 to -0.67
			Hip angle	80.99°±6.46	82.10°±6.30	t(75)= -2.13	-1.11°±4.55	0.037	-2.15 to -0.71
		Non-Dom.	FPPA	-2.46°±8.23	0.04°±7.65	t(74)= -2.93	-2.50°±7.37	0.004*	-4.19 to -0.80
			Hip angle	81.60°±6.38	83.72°±5.12	t(74)= -3.50	-2.11°±5.24	0.001*	-3.32 to -0.91

Table 4:6 Results of differences between pre-season & start-season performance for FPPA & hip angle

Start-season to end-season differences

Table 4:7 shows the results of statistical tests of change in performance between start-season and end-season.

Screening		*Leg*		*Start M ±SD*	*End M ±SD*	*Stat. test*	*Mean difference ±SD*	*P value*	*Confidence interval*
Start To End Change	*SLS*	Dom.	Hip angle	73.78°±8.11	73.52°±8.15	t(62)= 0.37	0.26°±5.57	0.73	-1.14 to 1.66
		Non-Dom.	Hip angle	75.67°±7.20	74.93°±7.15	t(62)= 0.90	0.74°±6.49	0.37	-0.89 to 2.37
	SLL	Dom.	FPPA	-1.76°±8.65	-1.49°±8.67	t(60)= -0.28	-0.27°±7.54	0.78	-2.20 to 1.66
			Hip angle	82.63°±6.10	83.66°±5.08	t(60)= -1.68	-1.03°±4.79	0.09	-2.26 to 0.20
		Non-Dom.	FPPA	-0.45°±7.58	2.31°±8.35	t(59)= -3.13	-2.76°±6.84	0.003*	-4.53 to -0.99
			Hip angle	83.52°±5.67	85.37°±5.67	t(59)= -3.11	-1.85°±4.62	0.003*	-3.05 to -0.66

Table 4:7 Results of difference between start-season & end-season performance for FPPA & hip angle

Pre-season to end-season differences

Table 4:8 shows the results of statistical tests of change in performance between pre-season and end-season.

Screening		*Leg*		*Pre M ±SD*	*End M ±SD*	*Stat. test*	*Mean difference ±SD*	*P value*	*Confidence interval*
Pre To End Change	*SLS*	Dom.	Hip angle	72.07°±8.89	73.47°±7.93	t(66)= -1.66	-1.40°±6.91	0.10	-3.09 to 0.29
		Non-Dom.	Hip angle	73.49°±8.81	74.94°±6.98	t(66)= -1.79	-1.46°±	0.07	-3.08 to 0.17
	SLL	Dom.	FPPA	-3.86°±7.93	-1.69°±8.52	t(64)= -2.73	-2.16°±6.38	0.008*	-3.75 to -0.58
			Hip angle	81.72°±5.97	83.55°±5.03	t(64)= -3.75	-1.83°±3.93	0.0005*	-2.80 to -0.86
		Non-Dom.	FPPA	-2.21°±8.48	2.54°±8.16	t(64)= -6.05	-4.74°±6.32	0.0005*	-6.31 to -3.17
			Hip angle	82.11°±5.97	85.39°±5.55	t(64)= -5.94	-3.27°±4.45	0.0005*	-4.38 to -2.17

Table 4:8 Results of difference between pre-season & end-season performance for FPPA & hip angle

In summary, the overall FPPA and hip angle performance change over time was statistically significant for both legs, dominant and non-dominant, in SLL but not in SLS. As to possible differences between any two screening sessions, there were no statistically significant performance differences of either FPPA or hip angle in both legs (dominant and non-dominant) in SLS.

In SLL, the non-dominant leg showed statistically significant difference between every two screening sessions (pre-season to start-season, start-season to end-season, and pre-season to end-season), whereas the dominant leg showed statistical significant difference both FPPA and hip angle between pre-season to end-season, and for FPPA in pre-season to start-season only.

4.4 Discussion

The aim of this study was to investigate the performance difference between legs (dominant and non-dominant) and the performance consistency over time (pre-, start- and end-season) in professional footballers using the functional tasks of SLS and SLL. In general, the results revealed statistically significant difference between legs (dominant and non-dominant) of knee FPPA in both SLS and SLL. There were also significant differences between screening sessions (over time) in knee FPPA and hip angle performance in SLL but not in SLS. However, no previous studies have investigated the lower limb performance differences over time although some studies have reported the differences between legs on a single screening occasion (Herrington, 2011; Herrington & Munro, 2010; Munro, Herrington, & Comfort, 2012; van der Harst, Gokeler, & Hof, 2007). These studies investigated the differences between right and left legs, and not between dominant and non-dominant legs (Herrington, 2011; Herrington & Munro, 2010; Munro, Herrington, & Comfort, 2012).

In the present study, the performance difference between legs (dominant and non-dominant) was clearly observed in all screening sessions in FPPA of SLL but not in hip angle. Also, the performance difference between legs was observed in SLS FPPA at pre-season and start-season screening whereas the difference between hip angles was observed at start-season only. The dominant leg FPPA was more valgus than the non-dominant leg in all screening sessions for both tasks. Moreover, the dominant hip was more adducted (had a smaller hip angle) than the non-dominant hip in all the screening sessions for both tasks. The difference between legs was always greater than the standard error of measurements, reported in the reliability study results in Table 3:7 when significant differences were found (see Table 4:3 and Table 4:4). In this study, we defined the leg dominance based on the player's answer to the question about which was their preferred kicking leg. However, the definition of leg dominance differs from one to another study in the literature (Svensson, Eckerman, Alricsson, Magounakis, & Werner, 2016). As mentioned previously, no previous studies have investigated the kinematic differences between legs according to leg dominance. In contrast, few studies have reported the knee and hip kinematic differences between legs according to localisation but found no significant differences between right and left legs in either sex (Herrington, 2011; Herrington & Munro, 2010; Munro, Herrington, & Comfort, 2012; van der Harst et al., 2007). Therefore, these results of performance difference between legs based on leg dominance constitute new information.

It is important to understand the reason behind the observed differences in performance between legs to understand its possible use in screening players who are at high risk of knee injuries. It can be hypothesized that the reason behind this difference in FPPA performance can be related to the muscle strength difference because it is one of the important internal factors that could affect performance (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008). However, current study did not collect the muscles strength, which leave this as a hypothesis only. Also, many previous studies have studied the muscle strength difference based on leg dominance (Burnie & Brodie, 1986; Masuda, Kikuhara, Takahashi, & Yamanaka, 2003; McCurdy & Langford, 2005). These studies examined the muscle strength differences between legs in both open and closed kinetic chain tasks but found no difference in muscle strength between legs in both hip and knee. Therefore, this hypothesis might explain our finding regarding the hip angle where no differences in performance between legs were observed in both tasks except in SLS at start-season screening (Burnie & Brodie, 1986; Masuda et al., 2003; McCurdy & Langford, 2005). However, the assumption that the muscle strength is the reason behind the performance difference in hip angle does not fit with the FPPA performance in both tasks because we observed significant differences in FPPA performance.

Previous studies found a negative correlation between muscle strength and knee valgus angle, which was correlated with the FPPA. Decreased hip abductors and external rotators muscle strength were correlated with increased hip adduction angle, knee valgus and FPPA (Claiborne et al., 2006; Lawrence et al., 2008; Willson et al., 2006). Claiborne et al. (2006) found a significant but only weak correlation (r = -0.37) between knee valgus angle and concentric hip abduction muscles strength but not eccentric during SLS. In contrast, Willson et al. (2006) found a significant weak-to-moderate correlation (r = 0.4) between FPPA and isometric hip external rotation strength but not with hip abduction strength. However, the contrasting results of previous studies, the difference in subject sex (female) from the current study (male) and the level of activity was not reported, making it difficult to support or neglect this hypothesis about the findings of the present study. Future studies are needed to examine the relationship between FPPA and hip angle performance, and lower limb muscles strength during common athletic tasks for both legs and compare them.

As to the performance differences over time (between sessions), SLS performance was consistent for both knee FPPA and hip adduction angle, which raises a question about SLS sensitivity when detecting changes and whether there is a performance ceiling effect or whether pre-season training has no impact on SLS performance. In contrast, SLL performance was significantly different over time for knee FPPA and hip angle. These different findings could be due to the nature of the tasks. The SLS task is a very simple test of knee alignment; SLL is more complex as the subject needs more muscle strength, activation and coordination to counter the ground reaction force during landing without losing balance or sustaining an injury (Blackburn & Padua, 2009; Cortes et al., 2007; Willson et al., 2006). However, knee FPPA of SLL decreased significantly from pre-screening (dom. -3.91°; non-dom. -2.43°) to end-season screening (dom. 1.49°; non-dom. 2.31°), meaning less knee valgus. Also, the hip angle of SLL increased significantly from pre-screening (dom. 81.65°; non-dom. 82.03°) to end-season screening (dom. 83.66°; non-dom. 85.37°), meaning less hip adduction. Therefore, both knee FPPA and hip angle are moving away from the high risk of injury at the end of the season based on the findings of previous studies that have linked greater dynamic knee valgus to knee injuries (Hewett et al., 2005).

It is important to understand the reasons behind this pattern of performance change over the pre-season period, especially as there is no previous research into the performance change over time. However, previous studies have investigated the relationship between muscle strength, knee FPPA and hip angle. This was discussed above in terms of the performance difference between legs. Another study found a significant reduction in knee FPPA for SLS after a four-week neuromuscular training programme, which might have mimicked the regular training of participating players in their teams as preparation for the season in the present study knowing that we did not collect any data about the training regimes (Olson, Chebny, Willson, Kernozek, & Straker, 2011). However, this assumption was made according to the regular training regimes for professional footballers but it is possible that some teams had done a plyometric training which might have secondary benefit on the score. In contrast, muscle fatigue could be another factor that affects the lower limb kinematics over time. Benjaminse et al. (2008) found a reduction in maximal knee valgus in single-leg stop-jump task after exercise-to-fatigue, which might be a reason for the present study finding of knee FPPA reduction from pre-season to end-season. Based on these studies it can be argued that the reason for the change in the present study findings over time could be due to the change in muscular strength either way during the sports season, though the previously presented argument above may refute this.

While this is the case, the study findings of knee kinematics differences between legs and over time confirm the study hypothesis (mentioned in the introduction) but it is difficult to confirm the reasons for these findings due to the variety of factors that can affect the lower limb kinematics. As for the study limitations, we can argue that participants whom we were unable to follow due to injury or absence at screening time were one of the limitations. This factor might affect the total mean value and the number of participants included in the statistical test knowing that the statistical tests exclude the participants who missed any sessions, as we did the screening on three different occasions over one sports season. Not taking the muscle strength measurement for each leg in each screening session with kinematics measurements might have contributed to the difficulty in giving a clear explanation of the study finding and the role of muscle strength. Moreover, the wide range of players' age (16–30) in the present study may have some effects on the results due to the increase in muscle strength and power assumed post-puberty (Barber-Westin et al., 2006; Wikholm & Bohannon, 1991), although some studies have reported no difference in knee valgus from pre- to post-puberty. Also, the expected percentage of immature players in this study is very low, which makes the age factor effects very minimal.

The importance of this study is the finding that examining the performance of knee FPPA and hip angle in one leg or on one occasion is not sufficient to determine which athletes are at high risk of lower limb injuries due to the difference in performance between legs and over time. A study of the relationship between injuries, and knee FPPA and hip angle performance difference between legs and over time, is necessary to confirm this hypothesis. Also, using the average value (mean) of performance difference between legs and over time to study the relationship with injuries could be misleading due to the variability in performance that was observed in this study even with equal average (mean) performance. This performance variability (within-subject and between-subjects) between legs and over time could be linked to the higher risk of injury. Future studies need to address the performance variability using the coefficient of variation to account for both the mean and standard deviation. Future studies also need to investigate the relationship between performance and performance variability with lower limb injuries. The issues of performance variability is addressed in the next chapter.

4.5 Conclusion

The study findings show the performance difference in SLS and SLL between dominant and non-dominant legs, and how it changes over time. The performance of knee FPPA was significantly different between the dominant and non-dominant leg in both tasks. The knee was more valgus and the hip more adducted in the dominant leg than in the non-dominant. The SLS performance was consistent over time whereas SLL was significantly different over time. These findings could suggest an important role for functional tasks performance variability in lower limb injuries and could open a new window in injury-prevention efforts. Also, the importance of this study is the finding that examining the performance of knee FPPA and hip angle in one leg or on one occasion might not be sufficient to determine which athletes are at high risk of lower limb injuries.

Chapter (5)

Variability In Biomechanical Tasks' Performance Across a Season

Chapter 5: Variability In Biomechanical Tasks' Performance Across a Season

5.1 Introduction

The athletic biomechanical tasks were used in both sports field and clinical settings. These tasks were used to predict athletes who are at higher risk of injury, and to assess the performance of those who are returning from injury (Delextrat & Cohen, 2008; Hewett et al., 2005; Munro, Herrington, & Carolan, 2012). The reliability and validity of using these tasks with different screening methods have been discussed in both the literature and the methodology sections. Although many studies have investigated the performance of these tasks and their possible relationship to lower limb injuries (Hewett et al., 2005; Myer et al., 2010; Willson et al., 2008), no studies have investigated the variability in kinematics performance, and the variability in performance and its possible relation to injuries.

The Oxford English Dictionary defines variability as a lack of consistency or fixed pattern ("The Oxford English Dictionary online," 2017). Therefore, variability in movement can be defined as the amount of movement change recorded between subsequent repetitions within an individual (Preatoni et al., 2013). Recently, sports biomechanists have become interested in movement variability, and have started to investigate its importance in the analysis of sports movements (Bartlett et al., 2007; Preatoni et al., 2010; Preatoni et al., 2013). Some studies have compared the performance-variability difference between symptomatic and asymptomatic individuals (Brown, Padua, Marshall, & Guskiewicz, 2009; Pollard et al., 2015). However, no studies have investigated the kinematics performance-variability difference of athletic tasks between legs (dominant vs. non-dominant), and over time.

The hypothesis of this study suggests that there is a performance-variability difference between legs and between sessions (over time). This hypothesis is derived from the importance of the performance consistency in athletic individuals where using the average performance is insufficient to show all the details of performance especially in high-level players (Preatoni et al., 2013). Also, reporting the performance average can sometimes be misleading because of extreme scores on average value, and the possibility for two players to have same average score but with different variability [(2, 3, 4, 5, 6; avg. = 4) and (4, 4, 4, 4, 4; avg. = 4)]. Moreover, according to our findings in chapter 4, which showed a performance difference between legs and over time, it is possible to find performance-variability differences between legs (dominant vs. non-dominant) and over time (pre-season, start-season and end-season). Additionally, the performance variability might have a role in sports injury prediction (James et al., 2000) because of the performance-variability difference found between injured and uninjured players retrospectively (Brown et al., 2009; Pollard et al., 2015). Therefore, it is important to examine the athletic tasks performance-variability difference within an individual "between legs and over time", and the performance-variability difference possible relationship to predict lower limb injuries prospectively.

5.2 Methods

5.2.1 Participants and Procedure

The same participants and procedure were used as described in chapter 4; please refer to chapter 4 sections 4.2.1 – 4.2.7.

5.2.2 Statistical analysis

The performance variability was calculated using the second-order coefficient of variation (V2) rather than the regular coefficient of variation (CV) due to its limitations (Kvålseth, 2016). These limitations have a significant impact on this study's results. This is because the coefficient of variation becomes problematic when the data are both positive and negative; it generally lacks an upper bound so that interpretations of V values become difficult and meaningless (Kvålseth, 2016). Also, it is highly sensitive to outliers, and it is very much affected by the mean and errors or changes in the mean (Kvålseth, 2016). In contrast, the second-order coefficient of variation takes on values between 0 and 1, making interpretations intuitively simple and meaningful (Kvålseth, 2016). A value of 1 means highest variability; a value of 0 means no variability.

All statistical tests were conducted using IBM SPSS Statistics software version 23. Two-way repeated measures ANOVA was used to examine performance variability interaction between time and limb using the FPPA V2 and hip angle V2 as outcome measures for each task (SLS, SLL). For both outcome variables, analysis of the standardised residuals showed that all the variables were not normally distributed, as assessed by the Shapiro–Wilk test of normality except start-season non-dominant SLS-hip angle, pre-season dominant SLL-hip angle, pre-season non-dominant SLL-hip angle, and start-season non-dominant SLL-hip angle. All statistical tests were carried out using non-parametric tests regardless of the four normally distributed variables, for better results reporting and interpretation knowing that this will not affect the results. As there is no non-parametric test alternative for two-way repeated measures ANOVA, a Friedman test was used which is the alternative for a one-way repeated measures ANOVA. This means that the interaction between time and limb cannot be calculated. Therefore, the Friedman test was used to assess the variability between sessions (over time).

Also, the Wilcoxon signed-rank test was used to compare differences between limbs (dominant and non-dominant), and between any two screening sessions (pre-season, start-season, end-season) if the Friedman test was statistically significant. Otherwise, no further tests were used if the Friedman test showed no statistically significant difference. The sign test was used as an alternative to the Wilcoxon test when the assumption of distribution shape of the differences between the two related groups was not symmetrical.

5.3 Results

5.3.1 Performance variability descriptive statistics

As the data was not normally distributed, the descriptive statistics show the medians (Mdn) of the second-order coefficient of variation (V2) and interquartile range (IQR) for FPPA and hip angle for both legs (dominant and non-dominant) in both tasks, for each screening session. V2 represents the variability, so for example V2 = 0.5 signifies 50% variability.

5.3.2 Pre-season performance variability

SLS

The dominant FPPA V2 (n = 88) has a median of 0.49 and IQR of 0.45, whereas the non-dominant FPPA V2 median is 0.58 and IQR of 0.50. Also, the dominant hip angle V2 (n = 88) has a median of 0.044 and IQR of 0.02, whereas the non-dominant hip angle V2 median is 0.035 and IQR of 0.03.

SLL

The dominant FPPA V2 (n = 88) has a median of 0.61 and IQR of 0.51, whereas the non-dominant FPPA V2 median is 0.70 and IQR of 0.47. Also, the dominant hip angle V2 (n = 88) has a median of 0.041 and IQR of 0.03, whereas the non-dominant hip angle V2 median is 0.046 and IQR of 0.03.

Figure 5:1 shows the median of pre-season performance variability (V2) for both tasks in both legs.

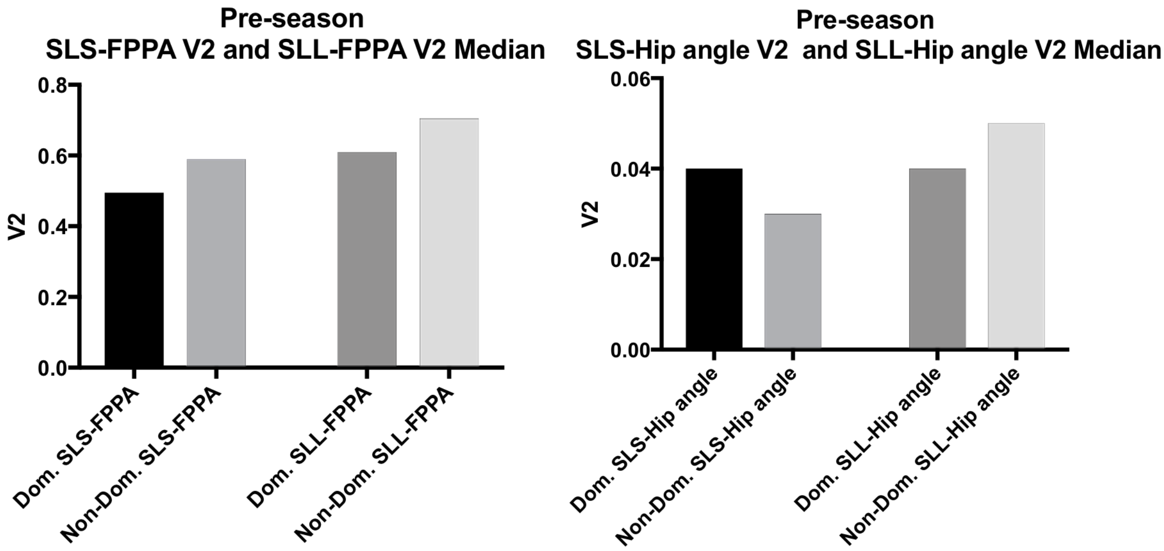

Figure 5:1 Pre-season performances variability (V2) for FPPA & hip angle

5.3.3 Start-season performance variability

SLS

The dominant FPPA V2 (n = 77) has a median of 0.49 and IQR of 0.48, whereas the non-dominant FPPA V2 median is 0.62 and IQR of 0.51. Also, the dominant hip angle V2 (n = 77) has a median of 0.040 and IQR of 0.03, whereas the non-dominant hip angle V2 median is 0.036 and IQR of 0.03.

SLL

The dominant FPPA V2 (n = 75) has a median of 0.65 and IQR of 0.44, whereas the non-dominant FPPA V2 median is 0.76 and IQR of 0.46. Also, the dominant hip angle V2 (n

= 75) has a median of 0.045 and IQR of 0.02, whereas the non-dominant hip angle V2 median is 0.043 and IQR of 0.03.

Figure 5:2 shows the median of start-season performance variability (V2) for both tasks in both legs.

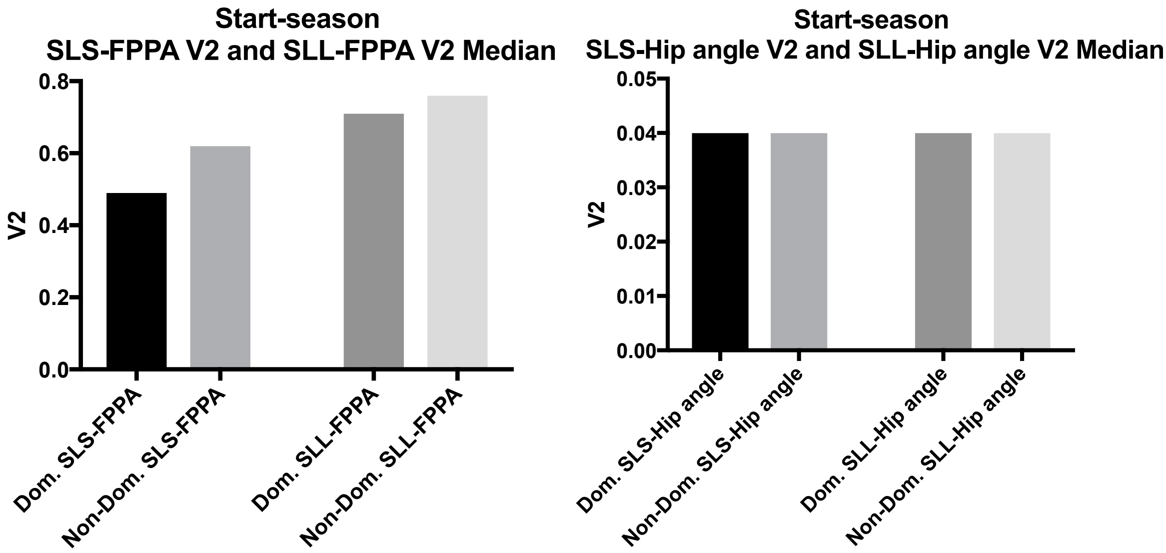

Figure 5:2 Start-season performances variability (V2) for FPPA & hip angle

5.3.4 End-season performance variability

SLS

The dominant FPPA V2 (n = 67) has a median of 0.52 and IQR of 0.54, whereas the non-dominant FPPA V2 median is 0.49 and IQR of 0.64. Also, the dominant hip angle V2 (n = 67) has a median of 0.040 and IQR of 0.03, whereas the non-dominant hip angle V2 median is 0.039 and IQR of 0.03.

SLL

The dominant FPPA V2 (n = 65) has a median of 0.68 and IQR of 0.30, whereas the non-dominant FPPA V2 median is 0.73 and IQR of 0.45. Also, the dominant hip angle V2 (n = 65) has a median of 0.038 and IQR of 0.02, whereas the non-dominant hip angle V2 median is 0.040 and IQR of 0.03. Figure 5:3 shows the median of end-season performance variability (V2) for both tasks in both legs.

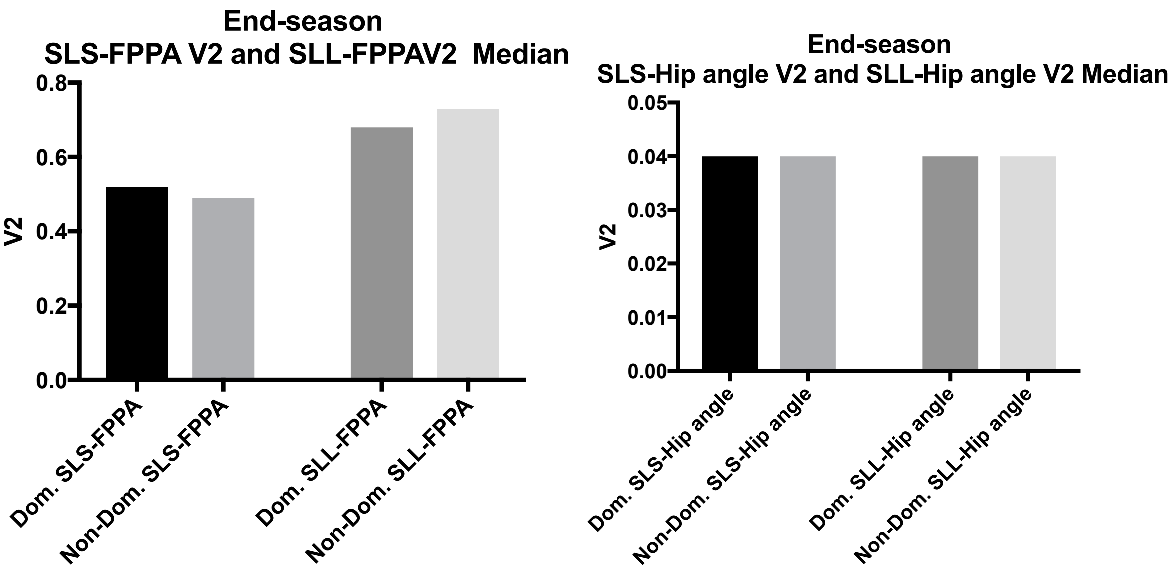

Figure 5:3 End-season performances variability (V2) for FPPA & hip angle

5.3.5 Within-session variability differences (Between limbs variability differences)

Wilcoxon signed-rank or sign tests were run to investigate the performance differences between limbs (dominant and non-dominant) for each screening time for each task as explained in the method part (section 5.2.2) previously. The alpha level of (α = 0.05) was adjusted to (α = 0.05/3 = 0.016) for multiple comparisons to avoid a type 1 error.

Pre-season

In SLS, a Wilcoxon signed-rank test showed no statistically significant difference for dominant SLS-FPPA V2 (Mdn = 0.49) compared with the non-dominant SLS-FPPA V2 (Mdn = 0.58) at the pre-season screening, Z = 1.29, p = 0.196, a median difference of -0.09. Also, there was no statistically significant difference for dominant SLS-hip angle V2 (Mdn = 0.044) compared with the non-dominant SLS-hip angle V2 (Mdn = 0.035) at the pre-season screening, Z = -0.031, p = 0.076, a median difference of -0.031.

In SLL, a Wilcoxon signed-rank test showed no statistically significant difference for dominant SLL-FPPA V2 (Mdn = 0.61) compared with the non-dominant SLL-FPPA V2 (Mdn = 0.70) at the pre-season screening, Z = 1.58, p = 0.114, a median difference of -0.09. Also, there was no statistically significant difference for dominant SLL-hip angle V2 (Mdn =

0.041) compared with the non-dominant SLL-hip angle V2 (Mdn = 0.046) at the pre-season screening, Z = 0.93, p = 0.351, a median difference of -0.005.

Start-season

In SLS, a Wilcoxon signed-rank test showed a statistically significant difference for dominant SLS-FPPA V2 (Mdn = 0.49) compared with the non-dominant SLS-FPPA V2 (Mdn = 0.62) at the start-season screening, Z = 2.72, p = 0.006, a median difference of -0.13. In contrast, a sign test showed that there was no statistically significant difference for the dominant SLS-hip angle V2 (Mdn= 0.040) compared with the non-dominant SLS-hip angle V2 (Mdn = 0.036) at the start-season screening, Z = -0.0.68, p = 0.494, a median difference of 0.004.

In SLL, a Wilcoxon signed-rank test showed no statistically significant difference for dominant SLL-FPPA V2 (Mdn = 0.65) compared with the non-dominant SLL-FPPA V2 (Mdn = 0.76) at the start-season screening, Z = 1.18, p = 0.237, a median difference of -0.11. Also, there was no statistically significant difference for dominant SLL-hip angle V2 (Mdn = 0.045) compared with the non-dominant SLL-hip angle V2 (Mdn = 0.043) at the start-season screening, Z = 0.14, p = 0.891, a median difference of 0.002.

End-season

In SLS, a Wilcoxon signed-rank test showed no statistically significant difference for dominant SLS-FPPA V2 (Mdn = 0.52) compared with the non-dominant SLS-FPPA V2 (Mdn = 0.49) at the end-season screening, Z = 0.28, p = 0.779, a median difference of 0.03. Also, there was no statistically significant difference for dominant SLS-hip angle V2 (Mdn = 0.040) compared with the non-dominant SLS-hip angle V2 (Mdn = 0.039) at the end-season screening, Z = 0.32, p = 0.750, a median difference of 0.001.

In SLL, a Wilcoxon signed-rank test showed no statistically significant difference for dominant SLL-FPPA V2 (Mdn = 0.68) compared with the non-dominant SLL-FPPA V2 (Mdn = 0.73) at the end-season screening, Z = 0.25, p = 0.806, a median difference of -0.05. Also, there was no statistically significant difference for dominant SLL-hip angle V2 (Mdn = 0.038) compared with the non-dominant SLL-hip angle V2 (Mdn = 0.040) at the end-season screening, Z = 0.49, p = 0.348, a median difference of -0.002.

Table 5:1 shows all the results of statistical between legs for FPPA V2 and hip angle V2 for both tasks.

Screening session			*Dom. leg Median*	*Non-Dom. leg Median*	*Stat. test*	*Median difference*	*P value*
Pre-season	*SLS*	FPPA V2	0.49	0.58	Z= 1.29	-0.09	p = 0.196
		Hip angle V2	0.044	0.035	Z= -1.78	-0.031	p = 0.076
	SLL	FPPA V2	0.61	0.70	Z= 1.58	-0.09	p = 0.114
		Hip angle V2	0.041	0.046	Z= 0.93	-0.005	p = 0.351
Start-season	*SLS*	FPPA V2	0.49	0.62	Z= 2.72	-0.13	p = 0.006*
		Hip angle V2	0.040	0.036	Z= -0.68	0.004	p = 0.494
	SLL	FPPA V2	0.65	0.76	Z= 1.18	-0.11	p = 0.237
		Hip angle V2	0.045	0.043	Z= 0.14	0.002	p = 0.891
End-season	*SLS*	FPPA V2	0.52	0.49	Z= 0.28	0.03	p = 0.779
		Hip angle V2	0.040	0.039	Z= 0.32	0.001	p = 0.750
	SLL	FPPA V2	0.68	0.73	Z= 0.25	-0.05	p = 0.806
		Hip angle V2	0.038	0.040	Z=0.94	-0.002	p = 0.348

Table 5:1 Results of statistical tests of difference between legs for FPPA V2 & hip angle V2

As a summary, in both tasks (SLS and SLL) there were no statistical significant differences in performance-variability of both FPPA and hip angle between the dominant and non-dominant leg in all screening sessions (Pre, start and end-season). The only significant difference between legs found in SLS - FPPA at start season screening were performance variability is more in the non-dominant leg.

5.3.6 Between-session variability differences (Over time variability differences)

Figure 5:4 shows the change in dominant leg performance over time (between sessions) for FPPA V2 and hip angle V2 for both tasks (SLS and SLL). Figure 5:5 shows the change in the non-dominant leg.

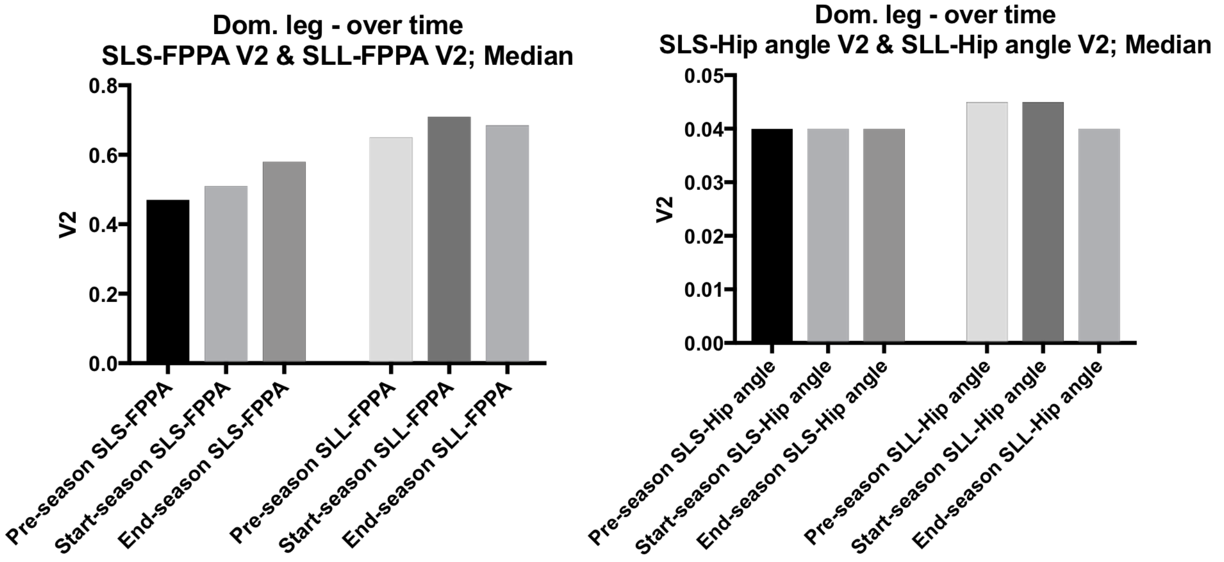

Figure 5:4 Dominant leg performances over time (between sessions) FPPA V2 & hip angle V2.

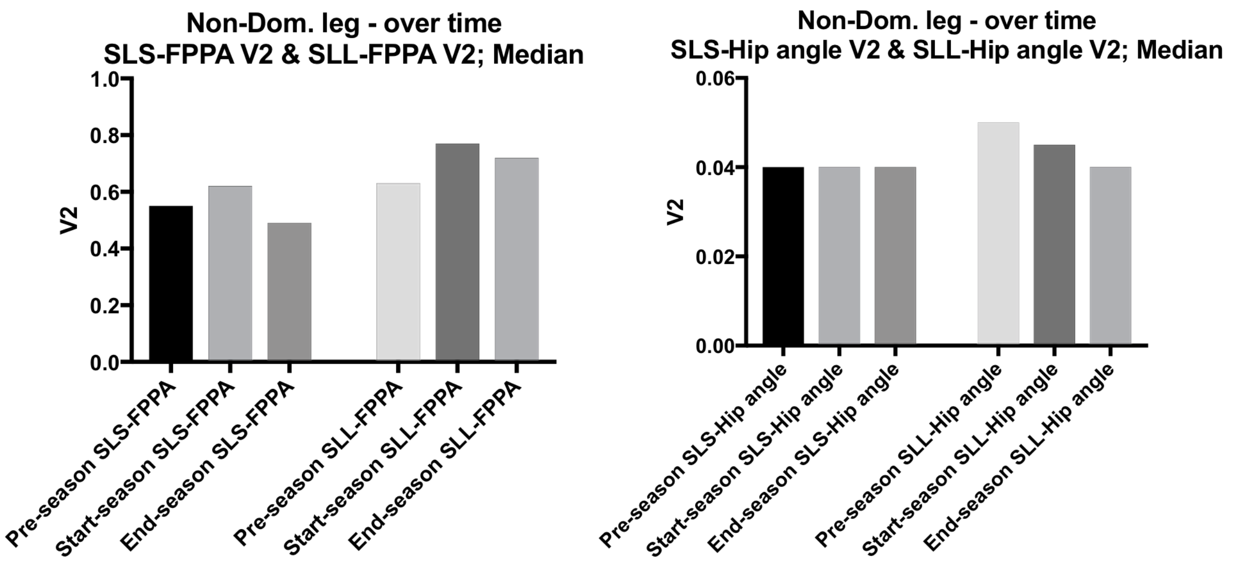

Figure 5:5 Non-dominant leg performances over time (between sessions) FPPA V2 & hip angle V2.

The Friedman test was run to investigate the performance variability change over time for each leg in both tasks (SLS and SLL) as explained in section 5.2.2. Table 5:2 shows all the results for the variability differences over time.

Screening		*Leg*	*Variable*	*Stat. tests*	*P value*
Between sessions (Over time)	*SLS*	Dom.	FPPA V2	$\chi2(2) = 4.03$	$p = 0.133$
			Hip angle V2	$\chi2(2) = .984$	$p = 0.611$
		Non-dom.	FPPA V2	$\chi2(2) = 2.89$	$p = 0.236$
			Hip angle V2	$\chi2(2) = 1.18$	$p = 0.556$
	SLL	Dom.	FPPA V2	$\chi2(2) = 1.60$	$p = 0.449$
			Hip angle V2	$\chi2(2) = 1.20$	$p = 0.549$
		Non-dom.	FPPA V2	$\chi2(2) = 2.43$	$p = 0.296$
			Hip angle V2	$\chi2(2) = 2.63$	$p = 0.268$

Table 5:2 Results of Friedman tests of difference over time for FPPA V2 & hip angle V2.

As the Friedman tests showed no statistical differences over time for all variables in both tasks, there is no need to assess the between-two-sessions variability changes, assuming that there is no statistically significant difference in variability between any two screening sessions.

In summary, the performance variability in FPPA and hip angle were consistent over time (along season) in both SLS and SLL ($p = 0.13–0.61$) meaning that there is no significant difference in variability through sport season.

5.4 Discussion

The objectives of this study were to examine the performance-variability difference between legs (dominant and non-dominant) and the performance-variability over time (pre-, start- and end-season) in footballers carrying out SLS and SLL athletic tasks. The study found no statistically significant difference of performance-variability between legs (dominant and non-dominant) of knee FPPA and hip angle in both tasks in all screening sessions except for knee FPPA at start-season in SLS. Also, there were no significant differences between screening sessions (over time) in knee FPPA and hip angle of performance-variability in all screening sessions in both tasks.

No previous studies have investigated the kinematic performance-variability difference between legs or over time (between sessions) using the common functional athletic tasks. However, a few studies have reported and discussed the movement variability in sport (Arshi et al., 2015; Bartlett et al., 2007; Bauer et al., 2017; Konig et al., 2016; Lockhart & Stergiou, 2013; Nordin & Dufek, 2017; Pollard et al., 2015; Preatoni et al., 2013; Smith et al., 2014). Some of these have used athletic tasks such as SLL, running, side-step cutting and single leg jump-landing to examine the performance-variability difference between symptomatic and asymptomatic subjects (Arshi et al., 2015; Brown et al., 2012; Nordin & Dufek, 2017; Pollard et al., 2015). Other studies have examined the gait variability difference between normal and pathological cases (Konig et al., 2016; Smith et al., 2014). All previous studies have used variables such as foot placement, step width, step length, stance time, swing time and jump height to examine the performance variability. However, none of these studies has reported or used the joints kinematics as a variable of measurement. Also, none has compared the performance-variability difference between legs and/or over time.

In the present study, there was no significant difference in performance-variability between legs (dominant and non-dominant) except the FPPA V2 of SLS at start-season screening ($p < 0.006$), which was not greater than the standard error of measurement. The difference between legs in SLS at start-season was 13% of 3.52° (FPPA avg. difference between legs), that is 0.45°, which is smaller than the standard error of measurement of SLS (1.41°) reported in the method chapter. Therefore, there is no significant difference in performance-variability in FPPA and hip angle between legs in both tasks. However, the FPPA was more variable in SLL than SLS, which could be due to the complexity of SLL over SLS (Blackburn & Padua, 2009; Cortes et al., 2007; Willson et al., 2006). Also, the performance-variability was consistent over time and there was no difference between sessions of FPPA and hip angle in both tasks. Therefore, these findings are new; no previous studies have reported these findings. However, the study findings of SLS and SLL performance variability reject the study hypothesis, which assumed a difference in performance-variability between legs and over time. This could mean that there is no clinical importance for the FPPA and hip angle variability since there was no statistical significant difference between legs of between screening sessions over season.

As for the study limitations, using the second-order coefficient of variation to assess the performance variability is not as sensitive as principal component analysis (PCA), which can be used only to assess the variability in the 3D system (Muniz & Nadal, 2009; Preatoni et al., 2013). However, the second-order coefficient of variation remains the best option for this study, compared with the regular coefficient of variation, for which the limitations and unsuitability for this study have been discussed in the method section (5.2.2). Also, one of the limitation of this study that we have used "5 trails" of testing while it is important to try to find the best number of trails that would give a precise picture about the variability. Unfortunately, trying to determine the right number of trails is a difficult process due to multiple causes (Preatoni et al., 2013). However, the sequential estimation procedure is used to calculate the right number of repetitions needed to obtain a sable mean when the successive mean deviations fall within a range around the overall average (Preatoni et al., 2013).

The importance of this study is the finding that performance variability is consistent over time and between legs. However, a further study is needed to examine the relationship between lower limb performance-variability and non-contact injuries because the present study's findings cannot confirm or reject this relationship.

5.5 Conclusion

The study findings show that there is no significant difference in performance-variability in SLS and SLL between dominant and non-dominant legs. Also, the performance-variability in SLS and SLL across the sports season was consistent. Therefore, the hypothesis of performance variability differs between legs and over time has been shown to be false. However, a study of the relationship between performance-variability difference and lower limb injuries is still needed.

Chapter (6)

Lower Limb Injuries and their Relation To Biomechanical Tasks Performance And Variability

Chapter 6: Lower Limb Injuries; and their Relation to Biomechanical Tasks' Performance and Variability

6.1 Introduction

Athletic biomechanical tasks have been used to predict athletes who were at higher risk of non-contact knee injuries, and to assess players who are returning from injury (Hewett et al., 2005; Munro, Herrington, & Carolan, 2012; Myer et al., 2010). These tasks have been found to be valid and reliable for this purpose as previously discussed in the literature review and method chapters. While there are few studies that have investigated lower limb kinematics during functional tasks, and its possible relations to lower-limb injuries (Hewett et al., 2005; Myer et al., 2010), there are no studies that have used the 2D technique to investigate the FPPA and hip adduction angle prospectively. Also, there are no studies that have examined the relationship of these tasks' performance-variability and their possible relation to injuries. The importance of this study using the 2D technique is enormous. This is because that 2D technique is simpler and more practical than the 3D system, which is usually used for this purpose. Also, the 2D technique is less expensive, portable and does not need a large space in which to examine the subject. This means that it can be used commonly in football clubs and clinics.

The hypotheses of this study suggest that SLS and SLL performance and performance-variability can predict the non-contact knee ligament injuries. Also, it suggests that SLS and SLL performance and performance-variability would change after injury. These hypotheses are derived based on previous research studies. For instance, Hewett et al. (2005) found that knee valgus performance can predict the non-contact knee injury using the 3D system and drop-jump landing task. Since there is a correlation between 2D and 3D systems using some tasks, and a correlation between these tasks' performance in a 2D system (Munro, Herrington, & Comfort, 2017), we expect that using theses task with 2D could predict non-contact knee injuries.

6.2 Methods

Same participants and procedures of previous studies in chapter 4 have been used; please refer to chapter 4 sections 4.2.1 to 4.2.8. However, from the 90 footballers, 2 players were excluded due to missing data. Therefore 88 footballers were included in this study, a total of 176 legs.

6.2.1 Tracking Injuries

All injuries that prevented a player from performing physical activity for more than five consecutive days have been reported by each club's licensed physiotherapist using the Tracking Injury Report Form "Appendix II". The period between pre-season and start-season screenings was called "Period one", while the period between start-season and end-season screenings was called "Period two". Therefore, injuries reported in each period can be studied to answer a specific study question.

6.2.2 Statistical testing

In answering the question of predicting non-contact knee ligament injuries, multivariate analysis could have been used. However, due to a limited number of recorded non-contact knee injuries (7 injuries), a descriptive analysis has been used alternatively.

In answering the second question about the performance and performance-variability change after injury, a Wilcoxon signed-rank test was used instead of a paired t-test. This is because the performance data of both groups' injured and uninjured players have some outliers, as assessed by boxplots. Moreover, the data of performance-variability of both groups was not normally distributed as assessed by Shapiro-Wilk's test ($p < .05$). A Sign test was used instead of the Wilcoxon signed-rank test in case of asymmetry distribution of the Wilcoxon result histogram. Finally, the alpha level was set to be .05 for all statistical tests that have been used to answer both questions.

6.3 Results

6.3.1 Lower-limb injuries

During this study, a total of 75 lower-limbs injuries were reported. Fifty-three (70.7%) of them were non-contact vs. twenty-two (29.3%) contact injuries. From the lower limb non-contact injuries, nineteen (35.8%) injuries were reported during period one, while thirty-four (64.2%) injuries during period two. The total number of non-contact knee ligaments' injuries was seven. Six injuries were reported during period one, and one injury during period two. These injuries included one complete tear ACL rupture, four patellofemoral pain syndrome, one medial collateral ligament and one lateral collateral ligament tear. More details about the reported injuries are presented in (Figure 6:1)

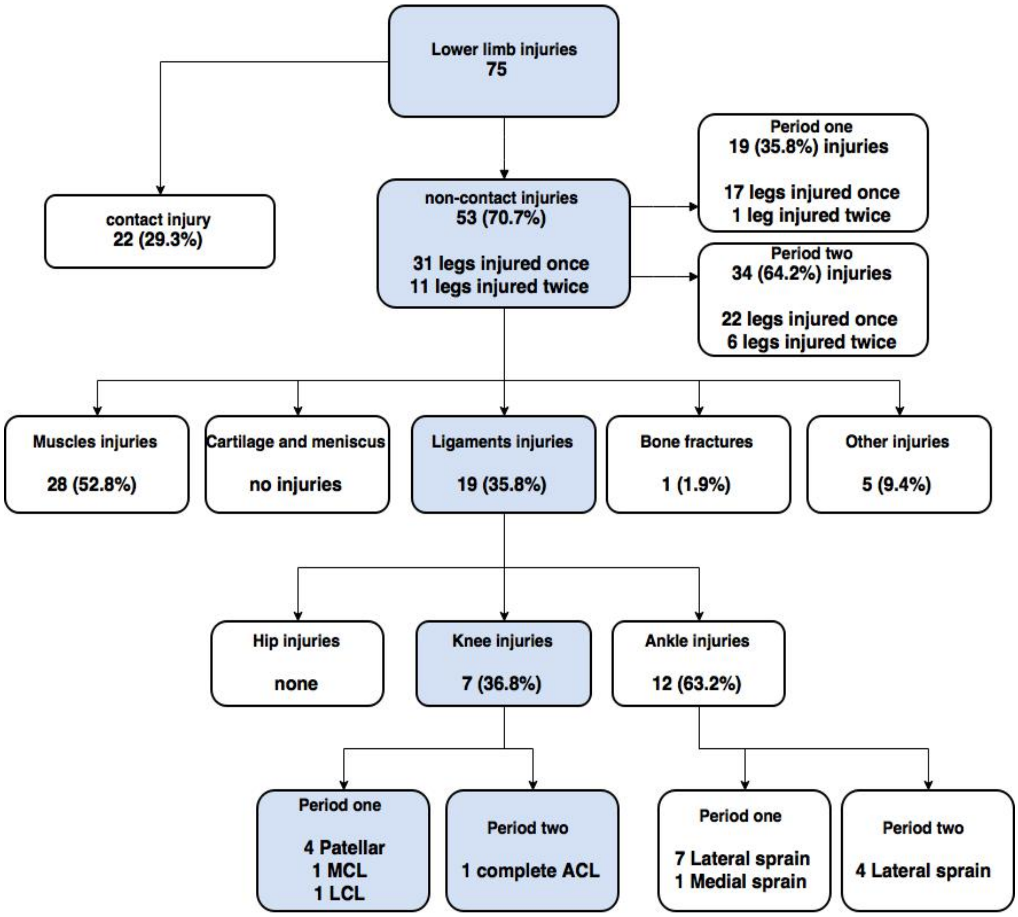

Figure 6:1 Reported lower limbs' injuries

6.3.2 Tasks' performance and performance-variability relation to injury

The tasks' performance and performance-variability relation to injury have been divided into two parts to answer two different questions. First, can we predict the non-contact knee ligament injuries before they occur? Second, how will the tasks' performance and performance-variability change after injury?

6.3.2.1 Predicting non-contact knee injuries:

As reported previously, six non-contact knee ligament injuries occurred during period one while only one injury occurred during period two. However, since there was no sufficient number of injuries to do a multivariate analysis, a descriptive analysis was carried out alternatively. Also, each period injury will be studied alone.

6.3.2.1.1 Period one injuries

Table 6:1 shows the tasks' performance median of injured and uninjured legs that occurred during period one. The table shows that the median of uninjured legs was more knee valgus and hip adducted than injured ones in both tasks. However, figures 6:2 and 6:3 were presented to show the actual values of the performance of knee and hip for all injured and uninjured legs. The figures show clearly that the distribution of injured leg performance is not different than the uninjured legs. This could mean that there were no legs more prone to injury comparing to others according to its performance of knee and hip adduction.

Screening session	*Performance*	*Injured leg Median*	*Uninjured leg Median*	*Median Difference*
Pre-season Screening	SLS-FPPA	2.74°	-2.07°	4.81°
	SLS-Hip angle	76.19°	74.76°	1.43°
	SLL-FPPA	-0.24°	-3.94°	3.70°
	SLL-Hip angle	83.45°	81.02°	2.43°

Table 6:1 Median scores of performance for injured and uninjured legs

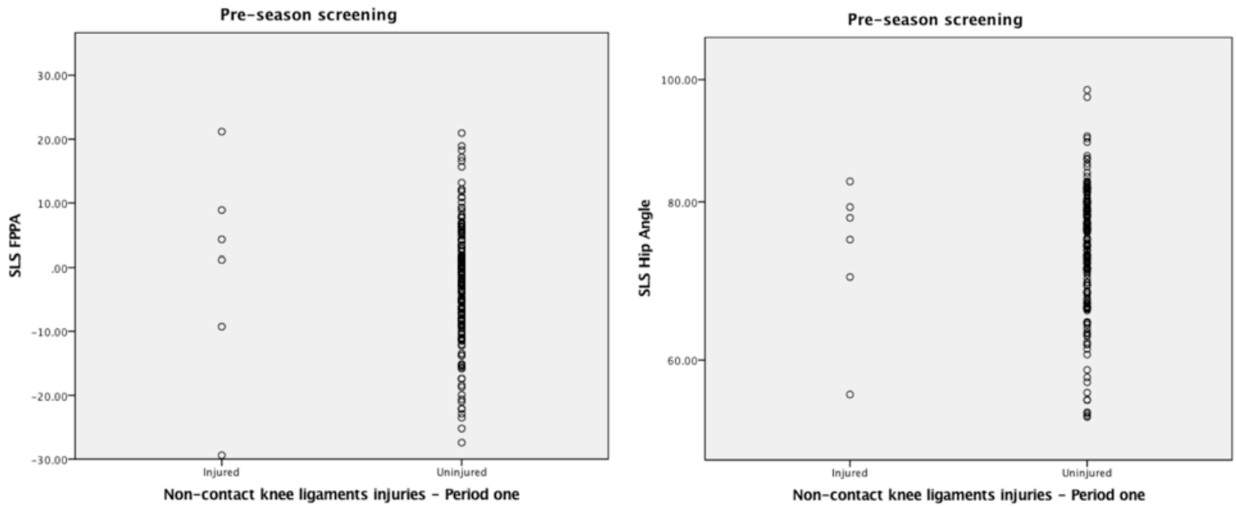

Figure 6:2 SLS performance at pre-season screening for injured vs. uninjured legs - Period one

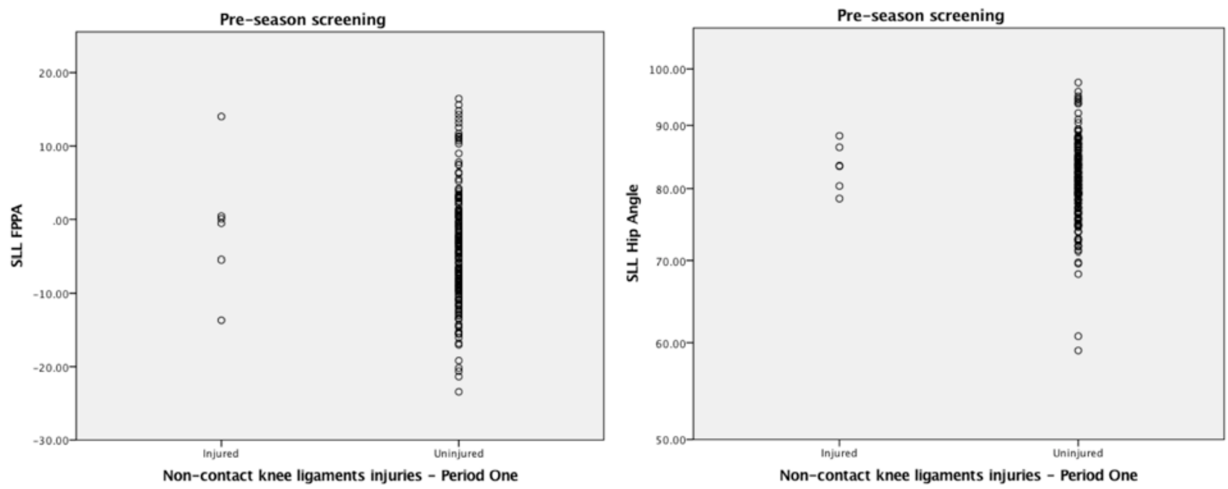

Figure 6:3 SLL performance at pre-season screening for injured vs. uninjured legs - Period one

Also, Table 6:2 shows the tasks' performance-variability median of injured and uninjured legs that occurred during period one. The table shows that the variability of injured legs was less in FPPA and hip angle except in FPPA during SLL. However, figures 6:4 and 6:5 were presented to show the actual values of the performance-variability of knee and hip for all injured and uninjured legs. The figures show clearly that the distribution of injured leg performance-variability is similar the uninjured legs. This could mean that there were no legs more prone to injury comparing to others according to its performance-variability of knee and hip adduction.

Screening session	*Performance-variability*	*Injured leg COV2*	*Uninjured leg COV2*	*COV2 Difference*
Pre-season Screening	SLS-FPPA	0.39	0.56	0.17
	SLS-Hip angle	0.033	0.042	0.009
	SLL-FPPA	0.94	0.65	0.29
	SLL-Hip angle	0.040	0.045	0.005

Table 6:2 Median scores of performance-variability for injured and uninjured legs

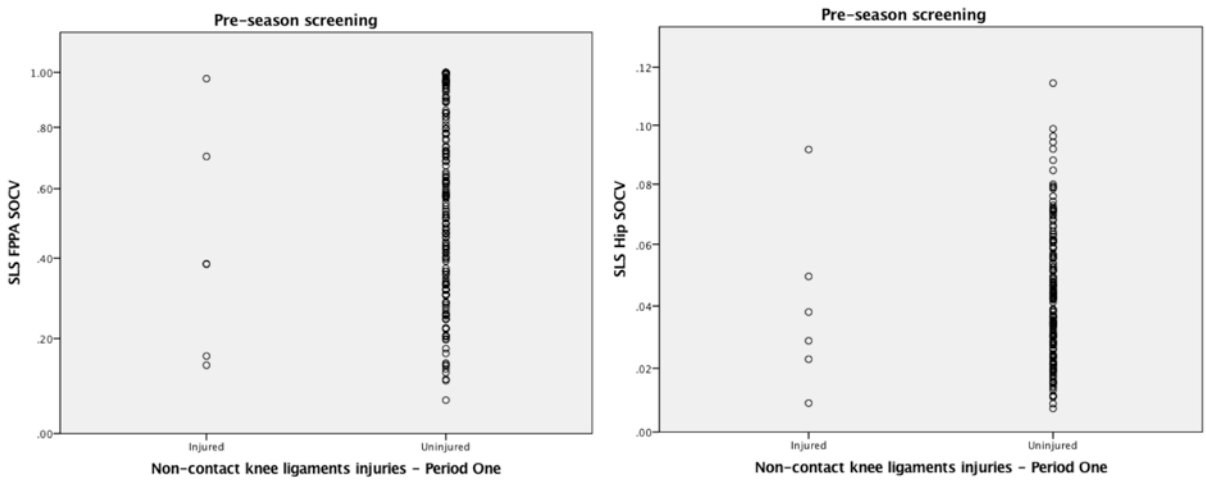

Figure 6:4 SLS performance-variability at pre-season screening for injured vs. uninjured legs - Period one

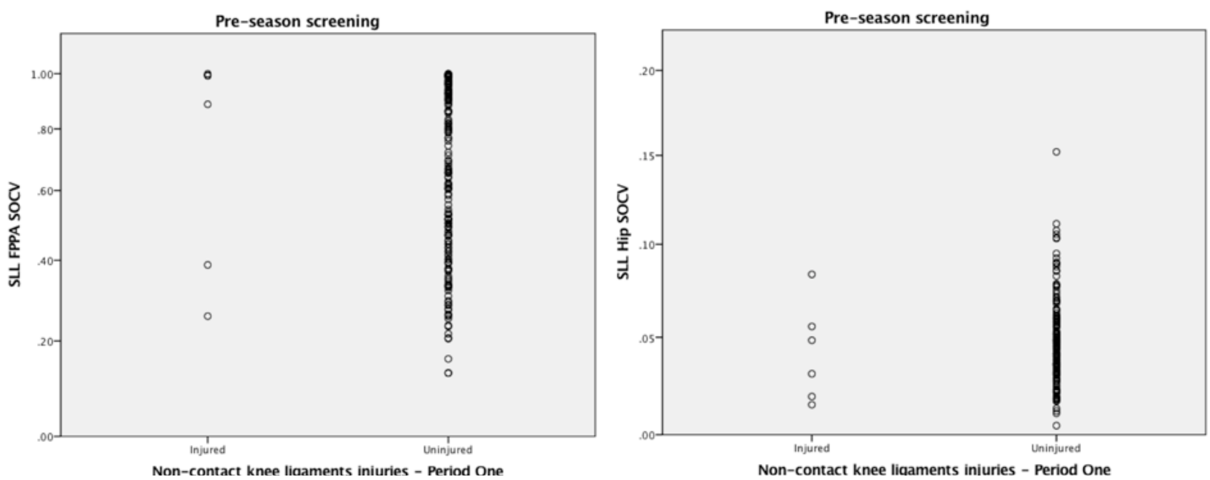

Figure 6:5 SLL performance-variability at pre-season screening for injured vs. uninjured legs - Period one

6.3.2.1.2 Period two injury

Studying the only injury that occurred during period two was impossible using the statistical tests. However, dot plots were used to visually examine the performance and performance-variability differences between this injured leg and uninjured legs. This comparison will be at pre-season screening only because the injured subject was not examined during start-season screening due to absence. Also, it is important to mention that this reported injury during period two was a complete ACL tear.

Figure 6:6 and Figure 6:7 show the performance of SLS and SLL respectively at pre-season screening where each dot represents one leg. The uninjured legs are on the right side of the dot plot while the injured leg is on the left side. In SLS, the injured leg FPPA score was within the top 11.93% of all legs (toward knee varus) while the hip angle score was within the top 33.52% of all legs (toward hip abduction). Also, in SLL, the injured leg FPPA score was within the top 9.1% of all legs (toward knee varus) while the hip angle score was within the top 37.5% of all legs (toward hip abduction).

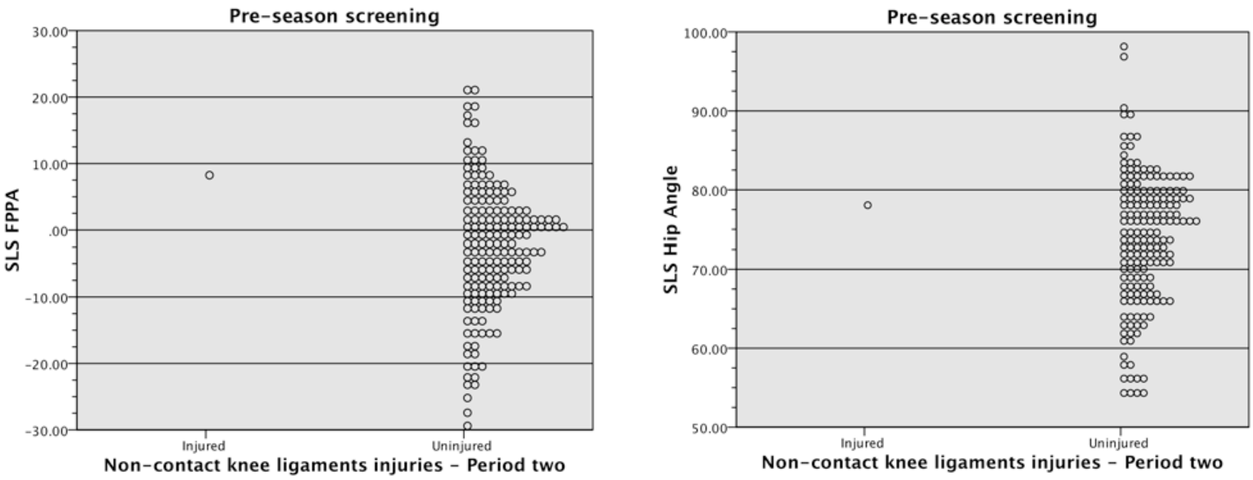

Figure 6:6 SLS performance at pre-season screening for injured vs. uninjured legs - Period two

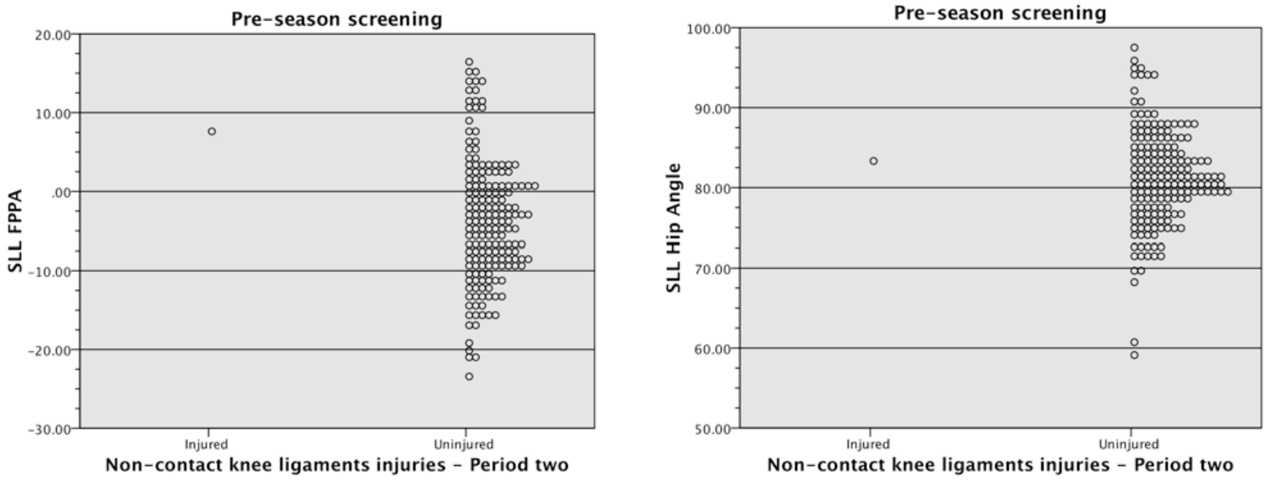

Figure 6:7 SLL performance at pre-season screening for injured vs. uninjured legs - Period two

On the other hand, Figure 6:8 and Figure 6:9 show the performance-variability of SLS and SLL respectively at pre-season screening where each dot represents one leg. The uninjured legs are on the right side of the dot plot while the injured leg is on the left side. In SLS, the injured leg FPPA was within the lowest 26.14% variability among all legs while the hip angle was within the lowest 3.98% variability among all legs. Also, in SLL, the injured leg FPPA was within the lowest 42.05% variability among all legs while the hip angle was within the lowest 47.73% variability among all legs.

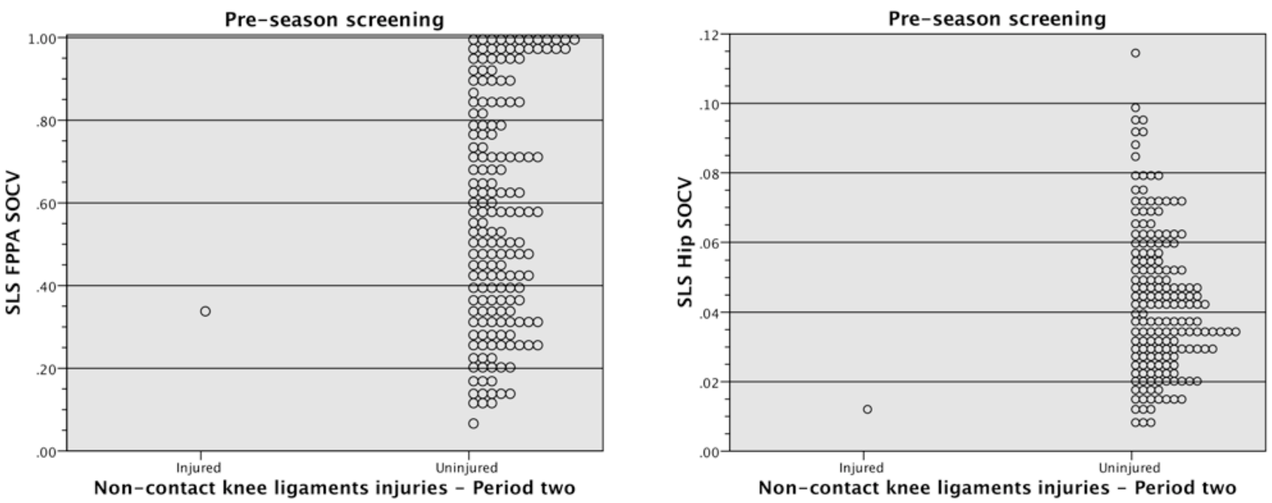

Figure 6:8 SLS performance-variability at pre-season screening for injured vs. uninjured legs - Period two

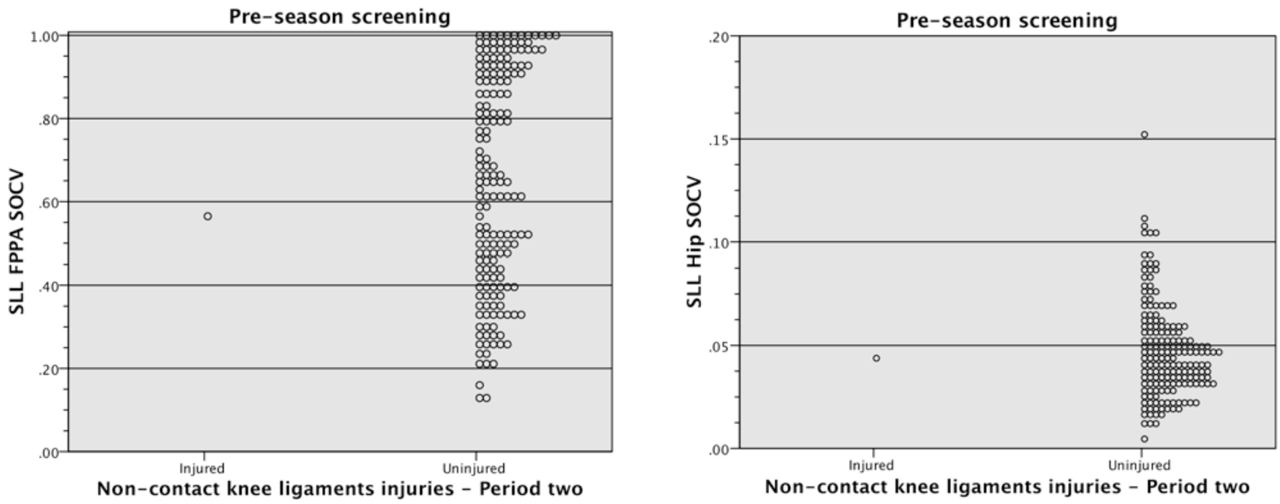

Figure 6:9 SLL performance-variability at pre-season screening for injured vs. uninjured legs - Period two

6.3.2.2 Performance and performance-variability change after injury:

As reported previously, six non-contact knee ligament injuries occurred during period one. Therefore, a pre-season screening was compared to a start-season screening for both injured and uninjured groups. This comparison was done to examine the performance and performance-variability change after injury, and how it differed in both groups.

Table 6:3 shows that the injured group's performance of SLS and SLL did not change significantly after injury. However, the uninjured group's performance of SLL did change from pre to start-season significantly, but not in SLS. Moreover, Table 6:4, shows that the performance-variability of SLS and SLL did not change from pre to start-season screening for both groups injured and uninjured.

Screening session	*Group*	*Performance (Angles)*	*Pre-season Screening Median* (Pre injury)	*Start-season Screening Median* (Post injury)	*Stat. test*	*Median Difference*	*P value*
SLS	Injured	SLS-FPPA	2.74°	2.60°	Z= 0.00	0.14°	1
		SLS-Hip angle	76.19°	78.19°	Z= 0.00	2°	1
	Uninjured	SLS-FPPA	-2.08°	-2.19°	Z= - 0.32	0.11°	0.75
		SLS-Hip angle	74.76°	74.36°	Z= 0.90	0.40°	0.37

SLL	Injured	SLL-FPPA	-0.24°	-3.03°	Z= 0.00	2.79°	1
		SLL-Hip angle	83.45°	82.35°	Z= -0.89	1.10°	0.38
	Uninjured	SLL-FPPA	-3.94°	-1.92°	Z= 4.29	2.02°	0.0005*
		SLL-Hip angle	81.02°	83.22°	Z= 4.20	2.20°	0.0005*

Table 6:3 Post injury performance change in SLS and SLL

Screening session	***Group***	***Performance-variability (SOCV)***	***Pre-season Screening Median* (Pre injury)**	***Start-season Screening Median* (Post injury)**	***Stat. test***	***Median Difference***	***P value***
SLS	Injured	SLS-FPPA	0.39	0.62	Z= 0.67	0.23	0.50
		SLS-Hip angle	0.033	0.042	Z= 0.00	0.009	1
	Uninjured	SLS-FPPA	0.56	0.55	Z= -0.37	0.01	0.71
		SLS-Hip angle	0.042	0.037	Z= -0.52	0.005	0.60
SLL	Injured	SLL-FPPA	0.94	0.70	Z= 0.00	0.24	1
		SLL-Hip angle	0.040	0.056	Z= 0.89	0.016	0.38
	Uninjured	SLL-FPPA	0.65	0.73	Z= 1.64	0.08	0.10
		SLL-Hip angle	0.045	0.043	Z= -1.11	0.002	0.27

Table 6:4 Post injury performance-variability change in SLS and SLL

6.4 Discussion

The main aim of this study was to examine the tasks' (SLS and SLL) performance and performance-variability in relation to non-contact knee ligament injuries. Two questions were answered to fulfil the study's main objectives. The first question was could the tasks' performance and performance-variability predict non-contact knee ligament injury? While the second question was, do the tasks' performance and performance-variability change after injury?

In regard to prediction of injuries, the number of injuries recorded during this study is insufficient to answer this question. Therefore, a descriptive analysis was done to look at the differences between the two groups of injured and uninjured legs. The findings of the study for period one showed almost similar performance and performance-variability of both tasks for FPPA and hip adduction angle in injured and uninjured legs at pre-season. In period two were only one complete ACL tear injury were recorded, results show that the performance of FPPA for the injured player was a varus (adducted) one, which was in the top 11.93% and 9.1% of all players for SLS and SLL respectively. Also, the performance of hip adduction angle for injured leg was toward abduction and in the top 33.52% and 37.5% of all legs in SLS and SLL respectively. Moreover, the performance-variability of FPPA for injured legs was in the lowest 26.14% and 42.05% of variability scores of all legs in SLS and SLL respectively. Also, the performance-variability of hip angle for injured leg was in the lowest 3.98% and 47.73% of variability scores of all legs in SLS and SLL respectively. The positioning of this players performance though interesting in where his performance lies in relation to his peers, in no way provides strong evidence of a potential relationship to injury. It might be with greater numbers of injury a more clear relationship develops, but equally this might not be the case.

Even though that the number of recorded non-contact knee injuries during this study make it impossible to answer the prediction ability of FPPA and hip angle, or even to study the statistical difference between the two groups, the descriptive analysis shows almost similar performance and performance-variability. Although that the first part of current study is from the lower levels of research hierarchy, it is still essential to compare it pervious studies. The current study findings are similar to the findings of Dingenen et al. (2015) who found no statistical significant difference in female FPPA between injured and uninjured legs during drop-jump tasks using the 2D technique. Dingenen et al. (2015) found a significant difference between injured and uninjured only when knee valgus and lateral trunk motion were combined together. However, current study results, which were obtained prospectively, were opposite to the study findings of Hewett et al. (2005), where they found a significant difference in knee valgus measures between injured and uninjured legs. Moreover, the current study found that injured legs have more knee varus than uninjured legs (not statistically), while the Hewett et al. (2005) study reported that injured legs knee valgus angles was more statistically significant. There are many differences between the current study and the Hewett et al. (2005) study, where they had examined the ACL injuries in females only using the drop-vertical-jump task in a 3D system. In contrast, the current study has been done on males and has included global knee ligament injuries using the 2D technique with SLS and SLL tasks. These differences might explain the findings differences but the rationale behind the current study using the SLS and SLL has been described in the methodology chapter. However, Messier et al. (2008) reported that behavioural and physiological risk factors are believed to interact with potential biomechanical mechanisms (knee joint forces and moments) to cause knee injury. Also, examining the risk factors of knee injuries is very difficult due to the complexity of how these factors interact with each other. This makes studying isolated risk factors practically impossible and difficult to determine the relative contributions of each factor to injury (Bartlett & Bussey, 2012). The current study had some limitations that had affected the results. These limitations include the number of obtained knee ligament injures and especially ACL injuries due to the need of a very large study sample. Also, the current study used the 2D technique, which is might be less sensitive in comparison to the 3D system that is known as the gold standard in biomechanical measurement. The reason for using the 2D technique in the current study was also clearly explained in the methodology chapter.

The second part of the current study was to examine the performance and performance-variability change after injury. The results showed that the performance of SLS and SLL in the injured group did not change significantly after injury, while the performance of SLL in the uninjured group did change from pre-season to start-season significantly, but did not change in SLS. Moreover, the performance-variability of SLS and SLL did not change from pre-season to start-season screening for both groups, injured and uninjured (before and after injury). Therefore, the important part of the result suggests that the performance of SLL in the injured group did not change after injury, when it should change (improve; less knee valgus and less hip adduction) according to our previous study findings in chapter four. The previous study in chapter four found that performance FPPA and hip adduction angle in SLL changed (improved) over time, but not in SLS. This means that the SLL task is more sensitive than that of SLS in predicting performance changes over time. These different findings could be due to the nature of the tasks. The SLS task is a very simple test of knee alignment while SLL is more complex, where the subject needs more muscles strength, activation and coordination to counter the ground reaction force during landing without losing balance or sustaining an injury (Blackburn & Padua, 2009; Cortes et al., 2007; Stefanyshyn et al., 2006; Willson et al., 2006). Also, the findings of the current study might mean that uninjured group performance did improve because they kept attending their regular training, which usually increases their muscles strength and coordination while the injured group lost some training sessions due to their injuries. However, there are some studies that have investigated the performance difference between non-contact knee injuries and asymptomatic legs retrospectively (Herrington, 2014; Stefanyshyn et al., 2006; Willson et al., 2008; Willson & Davis, 2008). These studies found that injured legs have more FPPA, knee valgus and/or hip adduction angle than asymptomatic ones. Nevertheless, this was not the same finding in the current study. These contrasting findings could be due to the difference in screening time. In the current study, the injured players were not screened immediately after the injury as was done in the previously mentioned studies. In the current study, the injured players were treated by their team’s physiotherapist and continued their regular season training until the specific day of screening, which could have been weeks after the injury was sustained. The time of screening in the current study was fixed for all participating teams and could not be changed because of its negative effects on the main PhD project aims.

The study findings of no change in performance-variability after injury might suggest that the performance-variability is not an appropriate tool to examine non-contact injuries since it failed to detect any difference between injured and uninjured legs prior or after injury. Also, this finding is supported by the findings of previous study in chapter five where no difference in performance-variability between legs or over time was detected. However, in answering the second question of the current study there were also some limitations. These limitations include the small number of obtained knee ligament injuries. Also, not examining the participants’ muscle strength made it difficult to know the exact reason behind the consistency in SLL task performance among injured legs in opposite to uninjured legs where performance has improved.

While this is the case, the study findings of lower-limb kinematics in relation to injuries failed to answer the study's first hypothesis of the ability of FPPA and hip angle performance and performance-variability in SLS and SLL to predict non-contact knee injuries. However, the study's second hypothesis of performance and performance-variability change after injury was rejected and found that uninjured footballers have improved while injured footballers did not change. The importance of these study findings is increasing the understanding that predicting the non-contact knee injuries is more difficult than previously thought. This is because there are many risk factors that could contribute to an injury occurrence. These factors include intrinsic (anatomical and hormonal) and extrinsic (play surface, shoe type and weather conditions) ones. However, the relative contribution of each factor is unknown and cannot be determined easily due to the inability to study each factor alone. Also, the findings of this study would indicate that larger sample size is needed to study the relation of the FPPA and hip angle with injury in prospective studies. Also, studying only one factor to predict the non-contact knee injuries is unlikely to be successfully because of the multifactorial nature of causes and the relatively large numbers of ways they could interact. Therefore, future studies with very large sample sizes need to be undertaken to predict the non-contact knee injuries. These studies need to try to combine more variables than just FPPA and hip adduction angle such as trunk lateral motion from a kinematic perspective, which might help to predict the non-contact knee ligaments injuries as found by Dingenen et al. (2015) which was published after finishing the data collection of current study. Moreover, trying to use other kinematics variable than peak angles like knee valgus displacement could be useful in predicting the non-contact knee ligament injuries as found in the most recent study by Holden et al. (2017). However, both these studies were done on the female populations, which might suggest that using the dynamic knee valgus to predict injury is a sex-specific technique for females only, as previously thought by Quatman and Hewett (2009). Thus, using a 3D system to screen male subjects prospectively might confirm or reject this hypothesis.

6.5 Conclusion

The study findings show that actual scores of FPPA and hip adduction angle performance and performance-variability of injured and uninjured legs are almost similar during SLS and SLL. However, the descriptive analysis that was used to look at the difference between injured an uninjured legs, is not sufficient to make any sold conclusion specifically in clinical setting. However, for the second part of the study, the FPPA and hip angle performance was found to be consistent in injured legs before and after injury while it had improved significantly in uninjured legs in SLL, but not in SLS. This means that the injury stopped performance improvement, which was occurring over the season in the injured legs. Therefore, it suggests that SLL is more sensitive than SLS to track footballers' performance over time (before and after injury), and it might play a role in footballers' decision to return to play after injury.

Chapter (7)

Summary, Conclusion and Recommendations for Future Work

Chapter 7: Summary, Conclusions and Recommendations for Future Work

7.1 Summary

Knee injuries are considered to be one of the most common athletic injuries. The two definitions used in the literature to define the injury, are based on time loss and the need for medical attention. In the United Kingdom, more than 388,000 new sports injuries were treated annually at A&E departments, as reported by the NHS (Digital, 2013). Also, more than 8.6 million sports and recreation-related injury episodes were reported every year in the United States (Sheu et al., 2016). Lower limb injuries were found to be 50-70% of all sports injuries reported (Hootman et al., 2007; Powell & Barber-Foss, 2000; Rauh et al., 2007), with knee injuries alone representing about 10-25% of sports injuries (Louw et al., 2008). Knee ligament injuries, though less frequent than some other injuries, are often more significant and considered sometimes catastrophic injuries because of the long recovery time and the inability sometimes to return to previous levels of performance post injury (Hewett, Di Stasi, & Myer, 2013; Louw et al., 2008).

Two D and 3D motion capture and analysis have been used to attempt to identify players who are at higher risk of getting non-contact knee injuries and to assess players who are returning to play following injury (Hewett et al., 2005; Myer et al., 2010). The 3D system has been regarded as the gold standard in biomechanics research (Munro, Herrington, & Carolan, 2012). However, the 3D system is considered to be complicated, time consuming and needs a lot of training for users; also, it is a very expensive system and needs a large, fixed workspace. These disadvantages have created a gap between research and clinical practice because most of the players screening would be done in sports clubs or primary clinics. In contrast, using the 2D system is more favorable because it is portable, less expensive, does not need a lot of training and requires less time to conduct. This means that it can be easily used in sport clubs and clinics regularly to track performance and identify players at high risk of non-contact injuries. However, the literature has inadequate information about the 2D assessment tool. Most importantly, the majority of the previous 2D studies are retrospective with no prospective study that investigates the ability of 2D technique to identify players who are at high risk of getting injured.

The way athletes move could increase the risk of injury (Bartlett & Bussey, 2012; Hewett et al., 2013). Using the nature of the movement pattern to identify high-risk players allows for targeted exercises to be used to control these movement patterns (Hewett et al., 2013) to decrease or prevent injury. The 2D FPPA has been used for this purpose during common athletic tasks (Herrington, 2014; Willson & Davis, 2008). The SLS and SLL tasks were found to be more appropriate for assessing players who are at higher risk of knee injuries. Both tasks are unilateral tasks, which helps to identify the risk for each leg alone as most injuries happen to one leg only. Moreover, previous studies have examined FPPA alone. Examining both FPPA and hip adduction angle might find more significant results, knowing that they are both key contributors to knee dynamic valgus. Also, more recent research found that SLS, SLL and drop-jump tasks using 2D technique are significantly correlated to each other, which confirms that SLS and SLL are most suitable tasks for this purpose (Munro et al., 2017). Another important point is that all previous studies that have investigated the lower limb biomechanics in relation to injury, have done so on one occasion only at the pre season. This might not be enough to understand the relationship between lower limb biomechanics and injury because the players' performance might not be consistent over the season; also the injury rate differs over the season which might be due to a performance change.

The Frontal Plane Projection Angle (FPPA) and hip adduction angle have been used in 2D technique for this purpose. However, previous studies have not investigated the difference in performance between dominant and non-dominant legs or the performance change over time. Also, there is no study that has examined the performance-variability difference between legs or over time. Both performance and performance-variability could be the reason for the different rate of lower limb injuries that happen at different times of the sport season, assuming that there is a link between performance and injury.

It is also critical to understand the within-session and between-sessions reliability of the 2D tool to establish the consistency of the results and the degree of measurement error. These will help in using the 2D technique confidently in repeated testing. Also, the validity of the 2D tool is important to find if the tool is accurately measuring what it's supposed to measure. Additionally, reporting the intra-rater and inter-rater values are important to make sure that we are getting the same degree of agreement among repeated administrations of same and different rater respectively. The reporting of the standard error of measurements will be very important to accurately determine that changes or improvements not due to measurements error. Also, reporting the small detectable difference (SDD) is important to determine that changes are actually due to a change in performance. Therefore, it can be used to make clinical decisions with confidence.

The aims of this thesis were to:

1. Review the literature of lower limb sport injuries mechanism and risk factors.
2. Review the literature of lower limb screening tools, which can identify the risk factors of injuries.
3. Assessing the reliability and validity of 2D video to assess SLS and SLL performance.
4. Assessing the SLS and SLL performance between legs and across season.
5. Assessing the performance-variability of individual lower limbs kinematics between legs and across season.
6. Examining the relationship between kinematic measures of lower limb joints and knee injury prevalence in male footballers, prospectively.

7.2 Conclusion

The first and second aims of this thesis were fulfilled by reviewing the literature for lower limb sport injury mechanisms and risk factors; also lower limb screening tools that have been used in identifying athletes who are at higher risk of getting injured in chapter 2 are reviewed. These reviews show that prospective studies investigating the relationship between lower limb kinematics and injury are limited in number and scope. Also, they have predominantly used the 3D system, which is considered to be the most advanced motion analysis system, but it needs a lot of training and a lot of working time to generate results. Therefore, the gap of the literature demands more research to look for simpler tools like the 2D technique that can be used easily in sport clubs and clinics to assess prospectively the lower limb relation to injury. Thus, this thesis aims to fill that gap and take the injury screening and tracking using 2D lower limb kinematics forward.

The criterion validity study in chapter 3, it was found that 2D FPPA has a large correlation with knee abduction angle in 3D ($r = 0.66$, $p < 0.008$) during SLS, but not in SLL ($r = 0.075$, $p < 0.79$). Also, the 2D hip adduction angle showed a very large correlation with the 3D hip adduction angle during SLS ($r = 0.81$, $p < 0.001$), and a large correlation during SLL ($r = 0.62$, $p < 0.013$). This means that compared to the 3D system, which is known as the gold standard in motion analysis, 2D technique has reasonable criterion validity as a tool for measuring SLS and SLL tasks.

The within-session reliability of both FPPA and hip adduction angle demonstrate good reliability with ICC ranging between (0.72 – 0.91) in SLS and SLL. Also, the between-session reliability of both FPPA and hip adduction angle demonstrated good reliability with ICC ranging between (ICC = 0.79 –0.86) in both tasks. Additionally, the intra-reliability found a very large correlation for FPPA and hip adduction angle in SLS ($r = 0.991$, $p < 0.001$), ($r = 0.987$, $p < 0.001$), and SLL ($r = 0.990$, $p < 0.001$), ($r = 0.967$, $p < 0.001$) respectively. Similarly, the inter-reliability found a very large correlation for FPPA and hip adduction angle in SLS ($r = 0.974$, $p < 0.001$), ($r = 0.962$, $p < 0.001$), and SLL ($r = 0.988$, $p < 0.001$), ($r = 0.985$, $p < 0.001$) respectively. Furthermore, the SEM for FPPA and hip angle for both tasks were reported. The SEM of FPPA during within-session and between-session screening ranged between 0.40° and 1.41° in both tasks. Also, the SEM of hip adduction angle during within-session and between-session screening ranged between 0.37° and 0.93° in both tasks. Therefore, the SLS and SLL were shown to be reliable tools to examine the performance difference between legs and the low measurement error should give confidence to track performance over time. The validity result was similar to previous studies, which found a moderate-to-strong relationship between FPPA and 3D knee abduction during SLS (Gwynne & Curran, 2014; Willson & Davis, 2008). The within-session and between-session reliability was found to be similar to previous findings by Munro, Herrington, and Carolan (2012) and Gwynne and Curran (2014) while the current study SEM was found to be slightly smaller. However, the novel finding, which was reported by the current study, is the validity of SLL, and inter, intra-rater reliability and SDD of both SLS and SLL.

Since the FPPA and hip adduction angle were found to be adequately valid and reliable using the 2D technique, the performance, performance-variability and its relation to injury studies were carried out using this method. The performance study in chapter 4, which has fulfilled the fourth aim, shows that there was a significant performance difference between dominant and non-dominant legs in FPPA in all screening sessions for both tasks. In all of screening sessions, the dominant leg knee FPPA was more valgus than the non-dominant leg. However, there was no difference in hip adduction angle between dominant and non-dominant legs in all screening sessions, except at the start-season screening for SLS.

The performance study has found that the FPPA and hip adduction angle for both legs changed (improved) significantly over the season when undertaking the SLL task, but not the SLS task. Also, the dominant leg FPPA improved from the pre- to start-season screening, while the non-dominant leg FPPA and hip adduction angle improved after each screening session. The performance study finding of the difference between legs is novel, since there was no previous studies that have investigated the performance difference between legs using the 2D technique according to leg dominancy. The reason behind the difference in FPPA performance between legs could be related to muscle strength difference because it is one of the important internal factors that could affect performance (Claiborne et al., 2006; Lawrence et al., 2008). Some previous studies found a negative correlation between muscle strength and knee valgus angle (Claiborne et al., 2006; Lawrence et al., 2008; Willson et al., 2006), which was correlated with the FPPA. This makes the dominant legs based on current study finding potentially more susceptible to injury. Therefore, this suggests that both legs should be screened individually when assessing the injury risk, and footballers possibly need to focus on increasing the dominant leg muscles strength to avoid injuries.

Also, this study was the first of its kind in tracking the biomechanical tasks performance over the season. These findings suggest that when tracking the footballer's lower-limb kinematics, it is important to examine both legs and to track them over the season. Also, only examining the footballer's performance at the pre-season point will not be enough, due to the performance change from pre-season to beginning of the season (start-season). The performance change (improvement, less knee FPPA) could be due to the improvement of the muscle power from the pre-season to the beginning of the season due to the effect of pre-season training. This observed improvement is in line with the injury rate changes during season in literature, which is usually at its highest at the pre-season (Bradley et al., 2002; Dodson et al., 2016) suggesting that when FPPA improved the injury rate decreased. However, this needs to be investigated in future research to find the relation between performance and muscle power, and injury.

Regarding the performance-variability study in chapter 5, which addressed the fifth aim, there were no previous studies that have investigated the kinematic performance-variability difference between legs or over time (between sessions) using the common functional athletic tasks. The knee FPPA and hip adduction angle variability were found to be consistent within-session and between-session for both tasks. These findings reject the hypothesis of individual performance-variability within-session and over time. The contribution of this study to the literature is that the individual performance-variability of lower limb kinematics within-session and between-session was not a significant factor that contributes to the variability of movement performance. Therefore, the performance-variability might not cause or contribute to injury.

With regard to the sixth aim, two relationship questions between kinematic measures of lower limb joints and knee injury were addressed in chapter 6. The first question was about the ability of 2D technique to predict the non-contact knee injuries. Unfortunately, the prospective study could not answer this question due to the limited number of obtained non-contact knee ligaments injures. The second question was about how the performance and performance-variability change after injury. The results revealed that the performance-variability of SLS and SLL did not change from pre- to start-season screening for both groups injured and uninjured. This finding supports the previous results of variability study of the incapability of individual kinematic performance-variability to affect the overall footballer movement performance. The results also showed that the SLL performance of uninjured legs group improved significantly from pre- to start-season. This was not the case for injured legs group were no performance change had been observed in both tasks. This could mean that the 2D technique might be a good tool in the SLL task to track footballers' performance over the season and to assess how regular training and injury affect their movement performance. This finding might open a new avenue of examining the change in lower limb kinematics over the season, and its relation to other factors like muscle strength and fatigue.

In respect to the clinical practice, the SLS and SLL can be used to track performance change of the knee and hip during SLS and SLL. The SEM has been reported for clinician to distinguish the clinical significant change from statistical change. Also, based on the findings of this thesis, it is important for the clinician to examine both legs independently and throughout the sport season due to the difference of performance between legs and between screening times. Moreover, the SLL found to be more sensitive in detecting changes comparing to the SLS task. Therefore, using SLL could be enough for this propose.

7.3 Recommendations for future work

Based on the results of this thesis and the subsequent discussion, several questions have been raised with regard to the future studies. The reliability study indicates that the 2D technique using the SLS and SLL tasks is a reliable method to assess the FPPA and hip angle. Also, the validity study indicates that 2D technique using the SLS and SLL tasks are a valid method to assess the FPPA and hip angle in SLS, as well as to assess the hip adduction angle in SLL compared with the 3D system. However, future research is needed to include other biomechanical tasks to be assessed for validity and reliability using the 2D technique like single drop-jump land. This would help to identify the most reliable task, and task that best correlates to the 3D system to identify players who are at higher risk of non-contact knee injuries. The lateral trunk motion should be added to the FPPA and hip angle performance, which might be more sensitive to predicting injury when combined together as shown by Dingenen et al. (2015) during the single-leg drop vertical jump.

Regarding the study of footballers' performance difference, the findings suggest the SLS task is not sensitive enough to track performance over the season. However, the SLL is sensitive and can be used for that purpose. This is because that SLL was able to detect the performance change over time while the SLS did not. The reason behind that could be due to the complexity of the SLL tasks where the subject needs more muscle strength, activation and coordination to counter the ground reaction force during landing without losing balance or sustaining an injury (Blackburn & Padua, 2009; Cortes et al., 2007; Willson et al., 2006). Future study is needed to examine simultaneously muscle power and lower limb kinematics to try to understand the link between each other and their relation to injury. Also, the study findings show that screening for lower limb kinematics in one leg or one occasion will not be enough to assess the performance due to the significant difference found between legs over the season. Therefore, both dominant and non-dominant legs need to be examined. Also, both pre-season and start-season screening need to be undertaken at least to track the kinematic performance, since the performance was significantly different between both occasions.

With regard to the variability study, the findings signify that individual kinematics performance-variability does not appear to exist between legs over time, or at least it cannot be measured using the 2D technique. Therefore, future study using the 3D system is needed to assess the variability, since it is more sensitive and recognised as the gold standard in motion analysis. Also, the future study needs to determine the right number of task repetitions needed to detect the variability before doing the actual study.

The prospective study of the biomechanical tasks performance and performance-variability relation to injury using the 2D technique could not answer this question due to the limited number of obtained non-contact knee ligaments injuries. Therefore, the study has recommended that a much greater number of participants is needed to allow future study to include more non-contact knee injuries. Moreover, very large number of subjects is needed to detect enough non-contact ACL injuries for more specific relationship study. Also, adding the trunk lateral motion to the FPPA and hip angle might be more sensitive in predicting the injuries as found by Dingenen et al. (2015) during the single-leg drop vertical jump task. Therefore, it is not definite that SLS and SLL using the 2D technique cannot predict the non-contact knee injuries.

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Appendices

General Appendices

PhD Timetable

Literature Review	October - December, 2014
Learning Agreement	December, 2014
Study 1, Validity (A) & Reliability (B)	January - April, 2015
Ethical Approval for Main Study	May - June, 2015
Interim Report Writing	June - July, 2015
Interim Assessment	22nd July, 2015
Pre-season collection	July, 2015
Start-season collection	August - Sep “week 1-4”; 2015
Video analysis for Pre & Start-season sessions,	Sep - Feb, 2015
End-season collection	March-April “week 36-40”; 2016
Writing up for internal assessment	May - June, 2016
Internal Assessment	27th June, 2016
Remaining video analysis	Aug - Dec, 2016
Statistical Analysis	Jan – March 2017
Writing up for thesis submission	March – July, 2017
Thesis submission	July, 2017

Supportive Course, Modules & Conference attended

No.	Date	Title	Type
1	8/10/2014	Electronic Resources for Researchers	Training course
2	9/10/2014	SOLAR Library search	Training course
3	9/10/2014	Finding Information for Your Study	Training course
4	9/10/2014	Developing Research Question	Training course
5	13/10/2014	Mind Mapping Software Training	Training course
6	14/10/2014	Effective Networking	Training course
7	15/10/2014	Introduction to PhD.	Part of Module
8	20/10/2014	Gold Open Access	Training course
9	22/10/2104	Electronic Resources for Researchers	Training course
10	23/10/2014	Overview of Critiquing Research Papers	Part of Module
11	10/11/2014	Literature Searching Practical & Queries	Part of Module
12	10/11/2014	Using Social Media and Technology to facilitate your PGR studied	Training course
13	12/11/2014	Doing a Literature Review	Training course
14	13/11/2014	Analysis, presentation, and interpretation of quantitative research	Part of Module
15	19/11/2014	Introduction to SPSS	Training course
16	19/11/2014	Gaining Informed Consent	Training course
17	20/11/2014	Referencing your work APA style	Training course
18	20/11/2014	LEAP Session	Training course
19	25/11/2014	Introduction to Endnote X7	Training course
20	27/11/2014	Advanced Statistics Data Analysis	Part of Module
21	01/12/2014	LEAP Higher – Academic Writing in English as a Second Language	Training course
22	03/12/2014	Writing the Thesis: Thinking about structure	Training course
23	03/12/2014	Quantitative research analysis with SPSS Advanced	Training course
24	04/12/2014	LEAP Higher – Academic Writing in English as a Second Language	Training course
25	11/12/2014	Dissemination and Publication of Research	Training course
26	15/12/2014	LEAP Higher – Academic Writing in English as a Second Language	Training course
27	16/12/2014	Good Citations for Health Sciences: Part1	Training course
28	09/01/2015	How to Use 3D system	
29	11-12/04/2015	Football Medicine Strategies for Player Care	Conference
30	15/04/2015	Sample size calculations and research	Part of Module
31	13-14/10/2016	Annual BASEM/FSEM Conference	Conference
32	13-15/05/2017	XXVI International Conference on Sports Rehabilitation and Traumatology	Conference

Ethical Approval Letter

University of Salford MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

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1 June 2015

Dear Msaad,

RE: ETHICS APPLICATION HSCR 15-27 – Biomechanical measures of lower limb predict non-contact knee injury risk factors in male athletes.

Based on the information you provided, I am pleased to inform you that application HSCR15-27 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible by contacting HSresearch@salford.ac.uk

Yours sincerely,

Sue McAndrew
Chair of the Research Ethics Panel

27/05/2015 – Version 2

Appendix 2

Information sheet

Information To Participate In A Research Project

You are invited to take part in this research study, which could provide important information for prevention of knee injuries in sport.

What is the project all about?

The study is looking at the relationship between lower limb kinematic variables during some typical athletic tasks, which may be linked to predicting knee injury risk factors in athletes.

Why have I been chosen?

You have been chosen as you are:

1. Athletic (participate in sport team as player).
2. Male aged from 16-30 years old.
3. Has not had a significant injury in the last 6 months to your lower limbs, which prevent you from attending 5 consecutive training sessions.
4. You are able to do single leg squat and single leg landing tasks independently without aids.

What will I have to do?

First: You will need to wear a loose pair of shorts or underwear to expose your lower limb and trunk in order to allow the video cameras to record you during the study.

Second: Your age, height and weight will be measures by the researcher.

Third: The researcher will attach a set of Photo-reflective markers directly to the skin on your lower limb joints as in Figure 1.

Fourth: You will then be required to preform two tasks, which are single leg squat and single leg landing for couple repetitions each task. "This part will be video recorded of your lower limbs and trunk only.

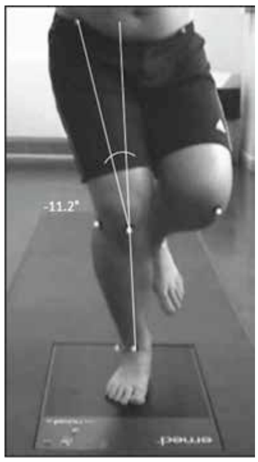


Figure 1

(*Adapted from Gwynne and Curran, 2014)*

All the study will take place inside the academy. The testing will not involve any exertion that you are not accustomed with through your current activity levels, and will be conducted over 4 sessions during one sport season, taking no longer than 5 minutes for each session.

All your information and data will remain confidential. The videos and electronic data will be protected by confidential password while other document will be stored safely in locked cabinet in the University of Salford. Also, your identity will be anonymous by codding your name and information. Finally, on completion of the study, your information and the video-recordings will be deleted and destroyed.

Is there any risk involved?

There is an inherent risk with any type of physical testing, however the testing for this study will be in a controlled environment and therefore any risks are minimal. The risk will not exceed the risk you might have during your sport training and competition.

Who will see my details and results?

All your information and data will remain confidential. The final results of the study will be available to you, and may be published.

- You are free to decide not to be in this trial or to drop out at any time.
- A minimum period of 24 hours will be set, between giving the information sheet to you and signing the consent form.
- Please feel free to ask any further questions about the nature or demands of the project at any time.

In case of you need to make any complaints: Please, follow this procedure:

First step: Contact this study team supervisor:

- **Lee Herrington PhD MCSP**
  Tel +44 (0) 7966872035
  Email: *L.C.Herrington@salford.ac.uk*

If you did not receive any response in 10 working days, or you were not satisfied with action has been done. Please, consider the second step.

Second step: Contact the Research & Innovation Manager

- **Anish Kurien MBA, PRINCE2, MSP**
  +44 (0) 161 295 5276
  Email: *a.kurien@salford.ac.uk*

Thank you for your consideration
Msaad Alzhrani

12/03/2015 – Version 1

Inclusion Criteria B

1. **Personal information**

Surname: …………………………… Forename(s): …………………………..

2. **Please, answer these questions carefully:**

What is your dominant leg?	☐ Right	☐ Left

Have you suffer a lower limb injury **in the last 6 months**?	☐ Yes	☐ No	
What joint?	☐ Hip	☐ Knee	☐ Ankle
What was the injury? For example; ACL, Ankle sprain, lateral knee ligament, etc.	……………………………………………….. ………………………………………………..		
What leg?	☐ Right	☐ Left	
Had this injury prevent you from attending **5 consecutive training sessions**?	☐ Yes	☐ No	

Have you undergo any lower limb surgery **in the last 6 months**?	☐ Yes	☐ No	
What joint?	☐ Hip	☐ Knee	☐ Ankle
What leg?	☐ Right	☐ Left	
What was the surgery for? For example; ACL reconstruction, Ankle sprain, lateral knee ligament, etc.	……………………………………………….. ………………………………………………..		

INFORMED CONSENT

The full details of the test have been explained to me. I am clear about what will be involved and I am aware of the purpose of the test, the potential benefits and the potential risks.

I know that I am not obliged to complete the test. I am free to stop the test at any point and for any reason.
The test results are confidential and will only be communicated to others once the data is fully anonymized, with no identifiable individual data.

I agree that the data being collected can be used within a research project (tick as appropriate): Yes ☐ No ☐

Name of Participant ………………..… Signature ……………………. Date…………………..

12/03/2015 – Version 1

Tracking Injury report Form

This form should be filled and submitted only for injuries that prevent player from attending five consecutive training sessions.

Player code: __________ **Date of injury:** ________________ **Time:** _____:______ am/pm

Injury occurred during?	☐ During Match ☐1st half ☐2nd half	☐ During Training ☐1st part ☐2nd part
	☐ Warm up for match	☐ Warm up for training
Is it Contact or Non-contact injury?	☐ Contact ☐ Non-contact	
Playground surface?	☐ Natural grass ☐ Artificial grass ☐ indoor	
Type of injury?	☐ New Injury ☐ Recurrent Injury	
Joint injured?	☐ Hip ☐ Knee ☐ Ankle	
What leg?	☐ Right ☐ Left	
What is the injury?	☐ Partial ACL tear ☐ Complete ACL tear ☐ Lateral Collateral ligament ☐ Medial Collateral ligament ☐ Meniscus injury ☐Medial ☐Lateral ☐ Patellar injury	
	☐ Lateral Ankle Sprain ☐ Medical Ankle Sprain	
	☐ Muscle Strain, What muscle? …………………………… ☐ Muscle Sprain, What muscle? …………………………… ☐ Bone Fracture, What bone? …………………………………	
	☐ Other than listed above Please specify,…………………………………………………	
How many days did the player take to return to previous activity level?	………………………………………………………………………	

Name:……………………………………………Signature :………………………………………………..

27/05/2015 – Version 1

Exposure Time Report Form

Club Name: .... Month/year: .... Contact person: ....

Tel: .... Mobile: .... E-mail: ....

Please, use these exposure codes to fill this form:

T = participation in training session (min)

M = participation in first team match (min)

RM = participation in reserve team match (min)

NT = participation in national team (min)

AT = absence from training because of injury

AM=absence from match because of injury

AN = absence due to other reason

Player's Code	Date									
01	Exposure code									
	Exposure duration in min									
02	Exposure code									
	Exposure duration in min									
03	Exposure code									
	Exposure duration in min									
04	Exposure code									
	Exposure duration in min									
05	Exposure code									
	Exposure duration in min									
06	Exposure code									
	Exposure duration in min									
07	Exposure code									
	Exposure duration in min									

This form might be expended as needed for larger players number

Subjects coding Form

Club's Name: .... Season year: …………………

Player's code	Player's club No.	First name	Family name	Player's code	Player's club No.	First name	Family name
A01				A31			
A02				A32			
A03				A33			
A04				A34			
A05				A35			
A06				A36			
A07				A37			
A08				A38			
A09				A39			
A10				A40			
A11				A41			
A12				A42			
A13				A43			
A14				A44			
A15				A45			
A16				A46			
A17				A47			
A18				A48			
A19				A49			
A20				A50			
A21				A51			
A22				A52			
A23				A53			
A24				A54			
A25				A55			
A26				A56			
A27				A57			
A28				A58			
A29				A59			
A30				A60			

This copy will be kept with the authorized person in the sport's club only

Subjects Characteristics Form

Club's Name: .... Season year: .... Contact person: ....

Tel: .... Mobile: .... E-mail: ....

Player's code	Height	Wight	Age	Dom. leg	Player's code	Height	Wight	Age	Dom. leg
A01					A31				
A02					A32				
A03					A33				
A04					A34				
A05					A35				
A06					A36				
A07					A37				
A08					A38				
A09					A39				
A10					A40				
A11					A41				
A12					A42				
A13					A43				
A14					A44				
A15					A45				
A16					A46				
A17					A47				
A18					A48				
A19					A49				
A20					A50				
A21					A51				
A22					A52				
A23					A53				
A24					A54				
A25					A55				
A26					A56				
A27					A57				
A28					A58				
A29					A59				
A30					A60				

Chapter 4 Appendices

Tests of Normality of Performance Residual

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Studentized Residual for PreSLS.DomFPPA	.052	60	.200*	.989	60	.885
Studentized Residual for StartSLS.DomFPPA	.078	60	.200*	.988	60	.800
Studentized Residual for EndSLS.DomFPPA	.069	60	.200*	.984	60	.605
Studentized Residual for PreSLS.Non.FPPA	.073	60	.200*	.982	60	.500
Studentized Residual for StartSLS.NonFPPA	.094	60	.200*	.980	60	.425
Studentized Residual for EndSLS.NonFPPA	.071	60	.200*	.973	60	.214
Studentized Residual for PreSLS.Dom.Hip	.069	60	.200*	.987	60	.784
Studentized Residual for StartSLS.DomHip	.047	60	.200*	.992	60	.973
Studentized Residual for EndSLS.DomHip	.072	60	.200*	.990	60	.903
Studentized Residual for PreSLS.Non.Hip	.056	60	.200*	.992	60	.953
Studentized Residual for StartSLS.NonHip	.067	60	.200*	.993	60	.977
Studentized Residual for EndSLS.NonHip	.076	60	.200*	.975	60	.247
Studentized Residual for PreSLL.DomFPPA	.059	60	.200*	.981	60	.454
Studentized Residual for StartSLL.DomFPPA	.078	60	.200*	.989	60	.863
Studentized Residual for EndSLL.DomFPPA	.071	60	.200*	.994	60	.988
Studentized Residual for PreSLL.NonFPPA	.072	60	.200*	.976	60	.282
Studentized Residual for StartSLL.NonFPPA	.114	60	.052	.976	60	.276
Studentized Residual for EndSLL.NonFPPA	.065	60	.200*	.990	60	.910

Studentized Residual for PreSLL.Dom.Hip	.107	60	.084	.966	60	.095
Studentized Residual for StartSLL.DomHip	.072	60	.200*	.981	60	.456
Studentized Residual for EndSLL.DomHip	.083	60	.200*	.988	60	.822
Studentized Residual for PreSLL.NonHip	.092	60	.200*	.983	60	.567
Studentized Residual for StartSLL.NonHip	.094	60	.200*	.978	60	.359
Studentized Residual for EndSLL.NonHip	.051	60	.200*	.986	60	.717

Studentised residuals outliers

with no scores greater than ± 3 standard deviations

	N	Minimum	Maximum
Studentized Residual for PreSLS.DomFPPA	63	-2.36	2.23
Studentized Residual for StartSLS.DomFPPA	63	-2.41	2.65
Studentized Residual for EndSLS.DomFPPA	63	-2.92	2.11
Studentized Residual for PreSLS.Non.FPPA	63	-2.38	2.18
Studentized Residual for StartSLS.NonFPPA	63	-2.20	1.96
Studentized Residual for EndSLS.NonFPPA	63	-2.58	2.07
Studentized Residual for PreSLS.Dom.Hip	63	-2.02	2.76
Studentized Residual for StartSLS.DomHip	63	-2.36	2.45
Studentized Residual for EndSLS.DomHip	63	-2.46	2.50
Studentized Residual for PreSLS.Non.Hip	63	-2.17	2.74
Studentized Residual for StartSLS.NonHip	63	-2.28	2.43
Studentized Residual for EndSLS.NonHip	63	-2.22	2.27

Studentized Residual for PreSLL.DomFPPA	60	-2.17	2.24
Studentized Residual for StartSLL.DomFPPA	60	-2.78	2.38
Studentized Residual for EndSLL.DomFPPA	60	-2.52	2.73
Studentized Residual for PreSLL.NonFPPA	60	-2.10	2.18
Studentized Residual for StartSLL.NonFPPA	60	-2.37	2.34
Studentized Residual for EndSLL.NonFPPA	60	-2.40	2.16
Studentized Residual for PreSLL.Dom.Hip	60	-1.69	2.31
Studentized Residual for StartSLL.DomHip	60	-2.03	2.30
Studentized Residual for EndSLL.DomHip	60	-2.53	2.84
Studentized Residual for PreSLL.NonHip	60	-2.26	2.54
Studentized Residual for StartSLL.NonHip	60	-2.90	2.39
Studentized Residual for EndSLL.NonHip	60	-2.06	2.23
Valid N (listwise)	60		

ANOVA repeated measure tests

SLS. Dom. And Non-dominant FPPA

Within-Subjects Factors

Measure: MEASURE_1

Time	Limb	Dependent Variable
1	1	PreSLS.DomFPPA
	2	PreSLS.Non.FPPA
2	1	StartSLS.DomFPPA
	2	StartSLS.NonFPPA
3	1	EndSLS.DomFPPA
	2	EndSLS.NonFPPA

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt
Time	.815	12.466	2	.002	.844	.865
Limb	1.000	.000	0	.	1.000	1.000
Time * Limb	.984	.992	2	.609	.984	1.000

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Epsilon Lower-bound
Time	.500
Limb	1.000
Time * Limb	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.[a]

a. Design: Intercept

Within Subjects Design: Time + Limb + Time * Limb

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Sphericity Assumed	73.648	2	36.824	.912	.404
	Greenhouse-Geisser	73.648	1.688	43.630	.912	.390
	Huynh-Feldt	73.648	1.730	42.569	.912	.392
	Lower-bound	73.648	1.000	73.648	.912	.343
Error(Time)	Sphericity Assumed	5005.798	124	40.369		
	Greenhouse-Geisser	5005.798	104.656	47.831		
	Huynh-Feldt	5005.798	107.265	46.668		
	Lower-bound	5005.798	62.000	80.739		
Limb	Sphericity Assumed	793.817	1	793.817	8.072	.006
	Greenhouse-Geisser	793.817	1.000	793.817	8.072	.006
	Huynh-Feldt	793.817	1.000	793.817	8.072	.006
	Lower-bound	793.817	1.000	793.817	8.072	.006
Error(Limb)	Sphericity Assumed	6097.394	62	98.345		
	Greenhouse-Geisser	6097.394	62.000	98.345		
	Huynh-Feldt	6097.394	62.000	98.345		
	Lower-bound	6097.394	62.000	98.345		
Time * Limb	Sphericity Assumed	108.790	2	54.395	1.856	.161
	Greenhouse-Geisser	108.790	1.968	55.273	1.856	.161
	Huynh-Feldt	108.790	2.000	54.395	1.856	.161
	Lower-bound	108.790	1.000	108.790	1.856	.178
Error(Time*Limb)	Sphericity Assumed	3635.038	124	29.315		
	Greenhouse-Geisser	3635.038	122.031	29.788		
	Huynh-Feldt	3635.038	124.000	29.315		
	Lower-bound	3635.038	62.000	58.630		

SLS. Dom. And Non-dominant Hip Angle

Within-Subjects Factors

Measure: MEASURE_1

Time	Limb	Dependent Variable
1	1	PreSLS.Dom.Hip
	2	PreSLS.Non.Hip
2	1	StartSLS.DomHip
	2	StartSLS.NonHip
3	1	EndSLS.DomHip
	2	EndSLS.NonHip

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt
Time	.884	7.541	2	.023	.896	.921
Limb	1.000	.000	0	.	1.000	1.000
Time * Limb	.988	.715	2	.699	.988	1.000

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Epsilon Lower-bound
Time	.500
Limb	1.000
Time * Limb	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.[a]

a. Design: Intercept

Within Subjects Design: Time + Limb + Time * Limb

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Sphericity Assumed	227.593	2	113.797	3.432	.035
	Greenhouse-Geisser	227.593	1.792	127.030	3.432	.041
	Huynh-Feldt	227.593	1.842	123.591	3.432	.039
	Lower-bound	227.593	1.000	227.593	3.432	.069
Error(Time)	Sphericity Assumed	4111.385	124	33.156		
	Greenhouse-Geisser	4111.385	111.082	37.012		
	Huynh-Feldt	4111.385	114.173	36.010		
	Lower-bound	4111.385	62.000	66.313		
Limb	Sphericity Assumed	240.686	1	240.686	5.111	.027
	Greenhouse-Geisser	240.686	1.000	240.686	5.111	.027
	Huynh-Feldt	240.686	1.000	240.686	5.111	.027
	Lower-bound	240.686	1.000	240.686	5.111	.027
Error(Limb)	Sphericity Assumed	2919.956	62	47.096		
	Greenhouse-Geisser	2919.956	62.000	47.096		
	Huynh-Feldt	2919.956	62.000	47.096		
	Lower-bound	2919.956	62.000	47.096		
Time * Limb	Sphericity Assumed	4.146	2	2.073	.168	.846
	Greenhouse-Geisser	4.146	1.977	2.097	.168	.843
	Huynh-Feldt	4.146	2.000	2.073	.168	.846
	Lower-bound	4.146	1.000	4.146	.168	.684
Error(Time*Limb)	Sphericity Assumed	1533.175	124	12.364		
	Greenhouse-Geisser	1533.175	122.572	12.508		
	Huynh-Feldt	1533.175	124.000	12.364		
	Lower-bound	1533.175	62.000	24.729		

SLL. Dom. And Non-dominant FPPA

Within-Subjects Factors

Measure: MEASURE_1

Time	Limb	Dependent Variable
1	1	PreSLL.DomFPPA
	2	PreSLL.NonFPPA
2	1	StartSLL.DomFPPA
	2	StartSLL.NonFPPA
3	1	EndSLL.DomFPPA
	2	EndSLL.NonFPPA

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt
Time	.949	3.008	2	.222	.952	.983
Limb	1.000	.000	0	.	1.000	1.000
Time * Limb	.964	2.102	2	.350	.966	.998

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Epsilon Lower-bound
Time	.500
Limb	1.000
Time * Limb	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.[a]

a. Design: Intercept

Within Subjects Design: Time + Limb + Time * Limb

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Sphericity Assumed	755.947	2	377.974	16.303	.000
	Greenhouse-Geisser	755.947	1.904	397.078	16.303	.000
	Huynh-Feldt	755.947	1.966	384.594	16.303	.000
	Lower-bound	755.947	1.000	755.947	16.303	.000
Error(Time)	Sphericity Assumed	2735.693	118	23.184		
	Greenhouse-Geisser	2735.693	112.323	24.356		
	Huynh-Feldt	2735.693	115.969	23.590		
	Lower-bound	2735.693	59.000	46.368		
Limb	Sphericity Assumed	432.864	1	432.864	3.756	.057
	Greenhouse-Geisser	432.864	1.000	432.864	3.756	.057
	Huynh-Feldt	432.864	1.000	432.864	3.756	.057
	Lower-bound	432.864	1.000	432.864	3.756	.057
Error(Limb)	Sphericity Assumed	6798.618	59	115.231		
	Greenhouse-Geisser	6798.618	59.000	115.231		
	Huynh-Feldt	6798.618	59.000	115.231		
	Lower-bound	6798.618	59.000	115.231		
Time * Limb	Sphericity Assumed	117.784	2	58.892	2.591	.079
	Greenhouse-Geisser	117.784	1.931	60.988	2.591	.081
	Huynh-Feldt	117.784	1.995	59.027	2.591	.079
	Lower-bound	117.784	1.000	117.784	2.591	.113
Error(Time*Limb)	Sphericity Assumed	2682.448	118	22.733		
	Greenhouse-Geisser	2682.448	113.945	23.542		
	Huynh-Feldt	2682.448	117.730	22.785		
	Lower-bound	2682.448	59.000	45.465		

SLL. Dom. And Non-dominant Hip Angle

Within-Subjects Factors

Measure: MEASURE_1

Time	Limb	Dependent Variable
1	1	PreSLL.Dom.Hip
	2	PreSLL.NonHip
2	1	StartSLL.DomHip
	2	StartSLL.NonHip
3	1	EndSLL.DomHip
	2	EndSLL.NonHip

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt
Time	.949	3.066	2	.216	.951	.982
Limb	1.000	.000	0	.	1.000	1.000
Time * Limb	.950	2.956	2	.228	.953	.984

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Epsilon Lower-bound
Time	.500
Limb	1.000
Time * Limb	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.[a]

a. Design: Intercept
Within Subjects Design: Time + Limb + Time * Limb

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Sphericity Assumed	436.326	2	218.163	17.927	.000
	Greenhouse-Geisser	436.326	1.902	229.395	17.927	.000
	Huynh-Feldt	436.326	1.964	222.193	17.927	.000
	Lower-bound	436.326	1.000	436.326	17.927	.000
Error(Time)	Sphericity Assumed	1436.038	118	12.170		
	Greenhouse-Geisser	1436.038	112.223	12.796		
	Huynh-Feldt	1436.038	115.860	12.395		
	Lower-bound	1436.038	59.000	24.340		
Limb	Sphericity Assumed	75.867	1	75.867	1.510	.224
	Greenhouse-Geisser	75.867	1.000	75.867	1.510	.224
	Huynh-Feldt	75.867	1.000	75.867	1.510	.224
	Lower-bound	75.867	1.000	75.867	1.510	.224
Error(Limb)	Sphericity Assumed	2964.605	59	50.248		
	Greenhouse-Geisser	2964.605	59.000	50.248		
	Huynh-Feldt	2964.605	59.000	50.248		
	Lower-bound	2964.605	59.000	50.248		
Time * Limb	Sphericity Assumed	25.745	2	12.872	1.373	.257
	Greenhouse-Geisser	25.745	1.905	13.512	1.373	.257
	Huynh-Feldt	25.745	1.967	13.087	1.373	.257
	Lower-bound	25.745	1.000	25.745	1.373	.246
Error(Time*Limb)	Sphericity Assumed	1106.035	118	9.373		
	Greenhouse-Geisser	1106.035	112.414	9.839		
	Huynh-Feldt	1106.035	116.068	9.529		
	Lower-bound	1106.035	59.000	18.746		

Chapter 5 Appendices

Tests of Normality for Performance-variability Residual

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Studentized Residual for PreSLS.DomFPPASOCV	.107	60	.085	.949	60	.014
Studentized Residual for StartSLS.DomFPPASOCV	.092	60	.200*	.952	60	.020
Studentized Residual for EndSLS.DomFPPASOCV	.109	60	.073	.920	60	.001
Studentized Residual for PreSLS.Non.FPPASOCV	.116	60	.043	.946	60	.010
Studentized Residual for StartSLS.NonFPPASOCV	.136	60	.007	.913	60	.000
Studentized Residual for EndSLS.NonFPPASOCV	.142	60	.004	.903	60	.000
Studentized Residual for PreSLS.Dom.HipSOCV	.098	60	.200*	.954	60	.023
Studentized Residual for StartSLS.DomHipSOCV	.143	60	.004	.911	60	.000
Studentized Residual for EndSLS.DomHipSOCV	.108	60	.081	.956	60	.029
Studentized Residual for PreSLS.Non.HipSOCV	.162	60	.000	.931	60	.002
Studentized Residual for StartSLS.NonHipSOCV	.088	60	.200*	.980	60	.449
Studentized Residual for EndSLS.NonHipSOCV	.153	60	.001	.920	60	.001
Studentized Residual for PreSLL.DomFPPASOCV	.119	60	.035	.928	60	.002
Studentized Residual for StartSLL.DomFPPASOCV	.111	60	.065	.914	60	.000
Studentized Residual for EndSLL.DomFPPASOCV	.083	60	.200*	.945	60	.009
Studentized Residual for PreSLL.NonFPPASOCV	.159	60	.001	.918	60	.001
Studentized Residual for StartSLL.NonFPPASOCV	.154	60	.001	.901	60	.000
Studentized Residual for EndSLL.NonFPPASOCV	.126	60	.019	.922	60	.001

Studentized Residual for PreSLL.Dom.HipSOCV	.088	60	.200*	.971	60	.159
Studentized Residual for StartSLL.DomHipSOCV	.092	60	.200*	.908	60	.000
Studentized Residual for EndSLL.DomHipSOCV	.128	60	.015	.919	60	.001
Studentized Residual for PreSLL.NonHipSOCV	.092	60	.200*	.963	60	.066
Studentized Residual for StartSLL.NonHipSOCV	.104	60	.168	.961	60	.052
Studentized Residual for EndSLL.NonHipSOCV	.108	60	.080	.932	60	.002

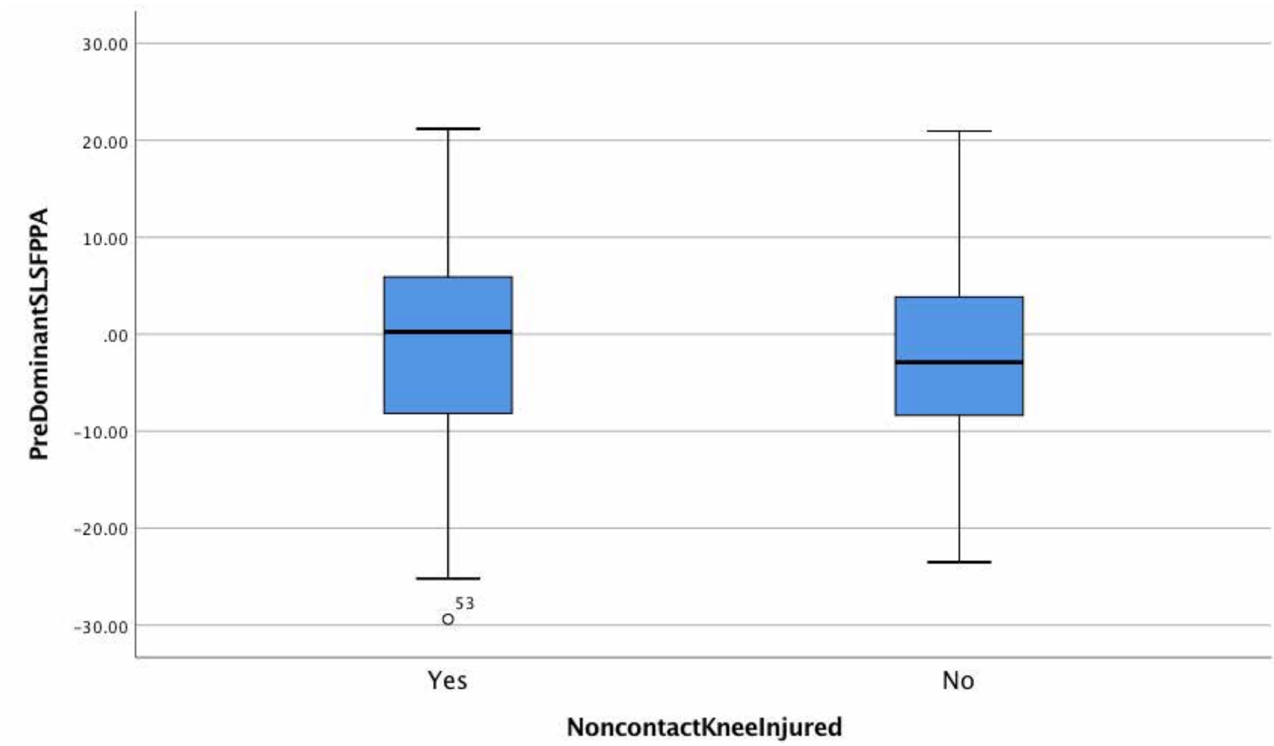
Chapter 6 Appendices

Tests of Normality for Performance Injured and Uninjured Groups

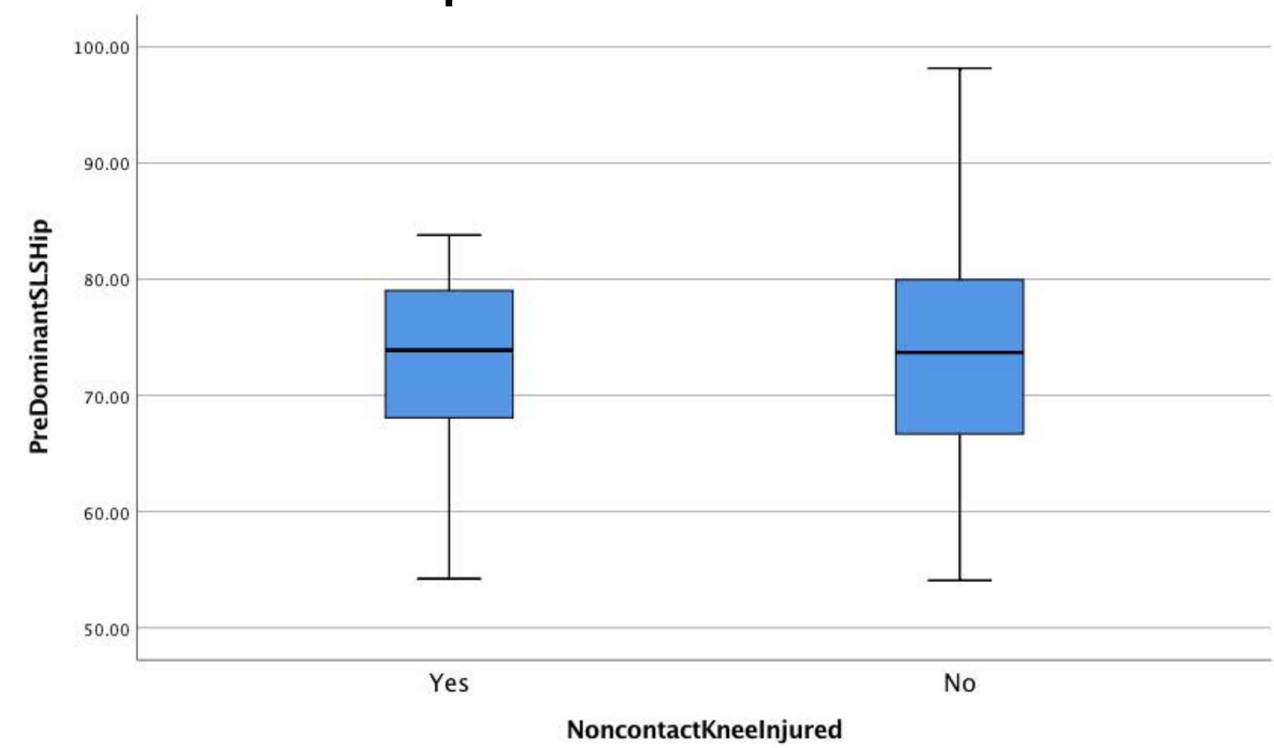
	NoncontactKneeInjured	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
PreDominantSLSFPPA	Yes	.135	17	.200*	.950	17	.462
	No	.049	103	.200*	.989	103	.561
PreDominantSLSHip	Yes	.144	17	.200*	.914	17	.116
	No	.054	103	.200*	.989	103	.558
PreDominantSLLFPPA	Yes	.116	17	.200*	.963	17	.685
	No	.070	103	.200*	.979	103	.097
PreDominantSLLHip	Yes	.115	17	.200*	.972	17	.846
	No	.046	103	.200*	.987	103	.407
StartDominantSLSFPPA	Yes	.193	17	.091	.922	17	.159
	No	.063	103	.200*	.995	103	.978
StartDominantSLSHip	Yes	.171	17	.200*	.933	17	.247
	No	.045	103	.200*	.993	103	.896
StartDominantSLLFPPA	Yes	.103	17	.200*	.975	17	.904
	No	.052	103	.200*	.994	103	.928
StartDominantSLLHip	Yes	.188	17	.113	.943	17	.356
	No	.078	103	.136	.986	103	.328
EndDominantSLSFPPA	Yes	.203	17	.060	.921	17	.156
	No	.040	103	.200*	.993	103	.883
EndDominantSLSHip	Yes	.148	17	.200*	.948	17	.433
	No	.052	103	.200*	.991	103	.690
EndDominantSLLFPPA	Yes	.138	17	.200*	.938	17	.292
	No	.054	103	.200*	.995	103	.974
EndDominantSLLHip	Yes	.101	17	.200*	.979	17	.943
	No	.053	103	.200*	.986	103	.366

Performance Outliers
Injured and Uninjured Groups

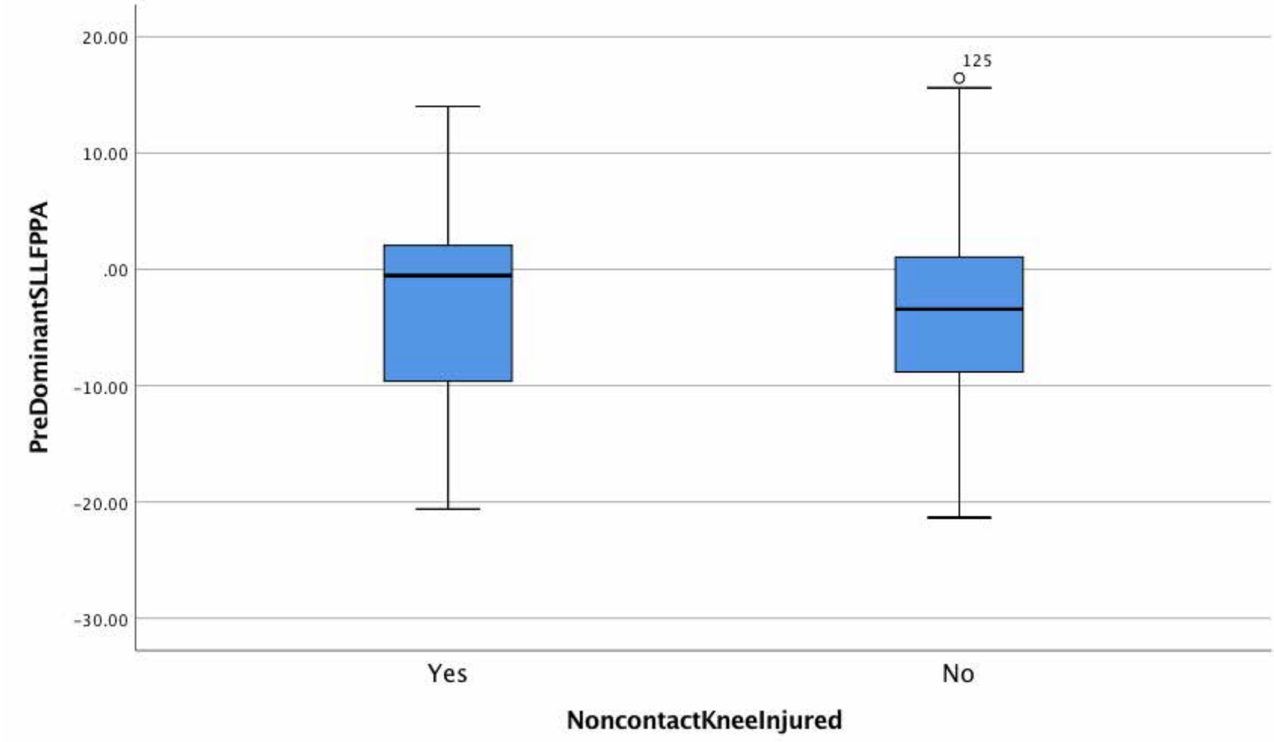
PreDominantSLSFPPA



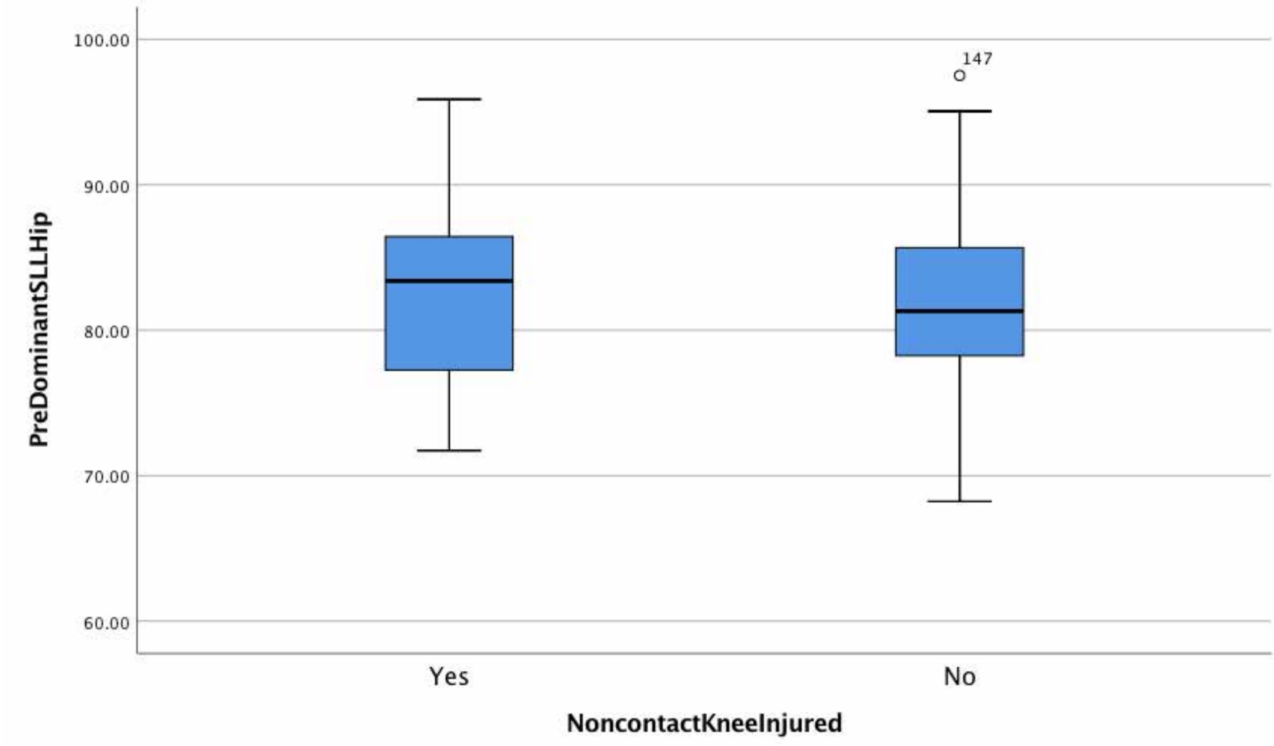
PreDominantSLSHip



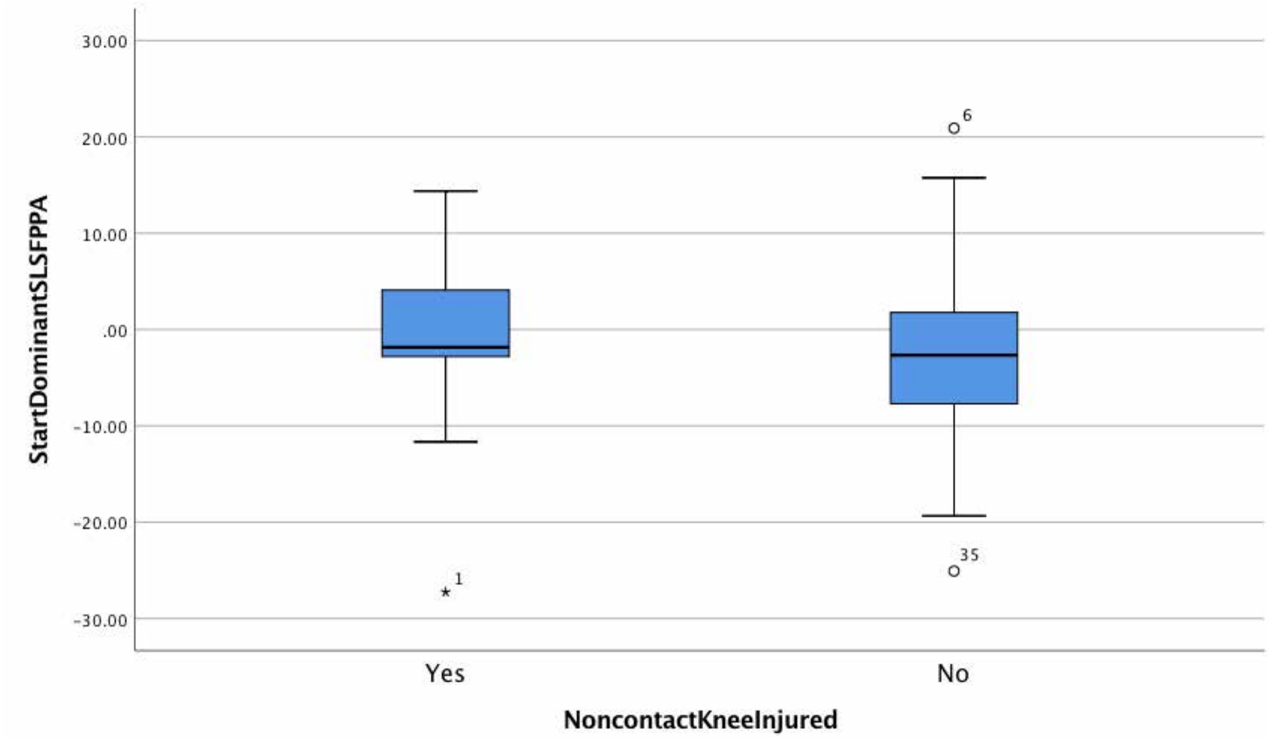
PreDominantSLLFPPA



PreDominantSLLHip



StartDominantSLSFPPA



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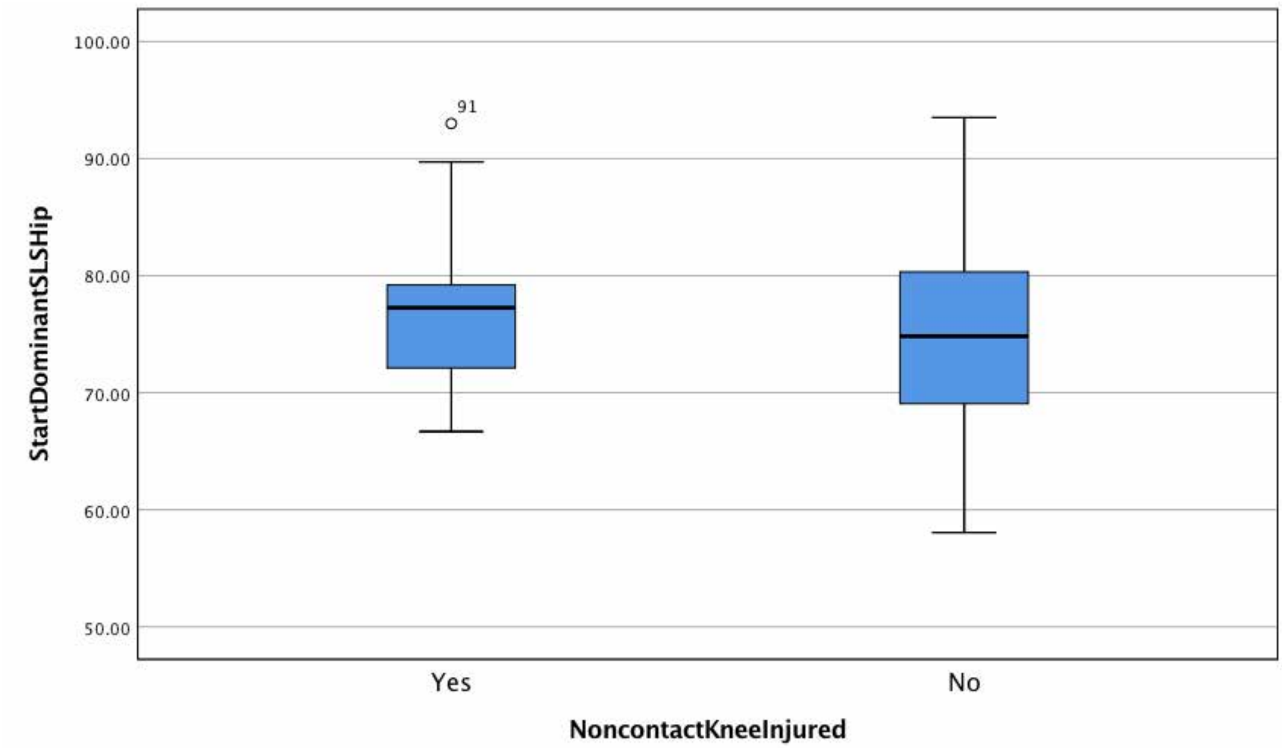

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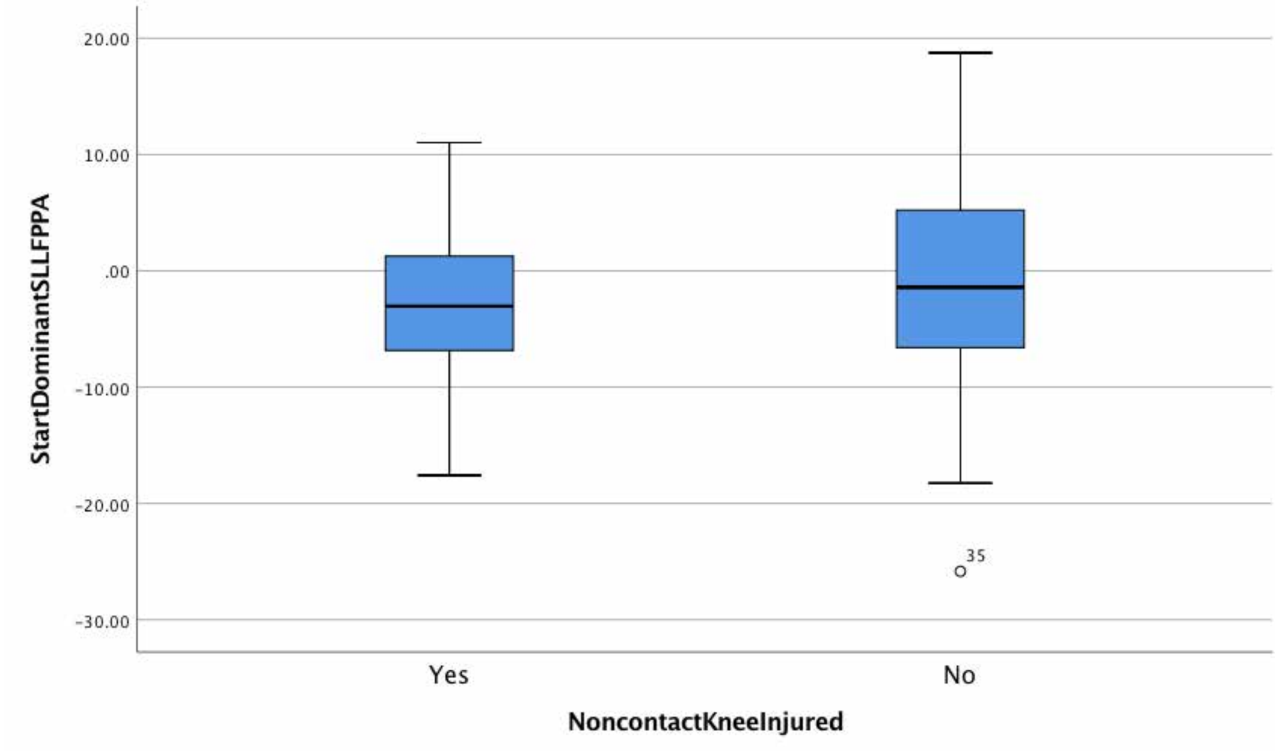

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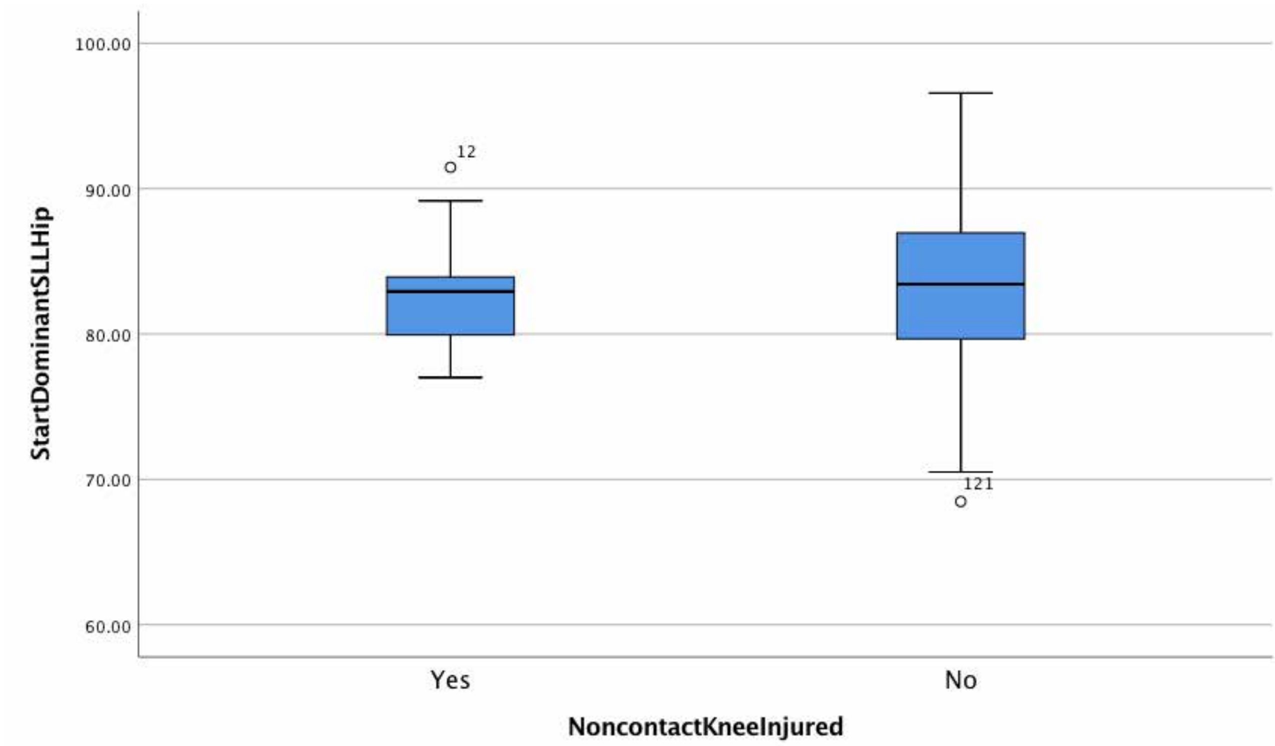

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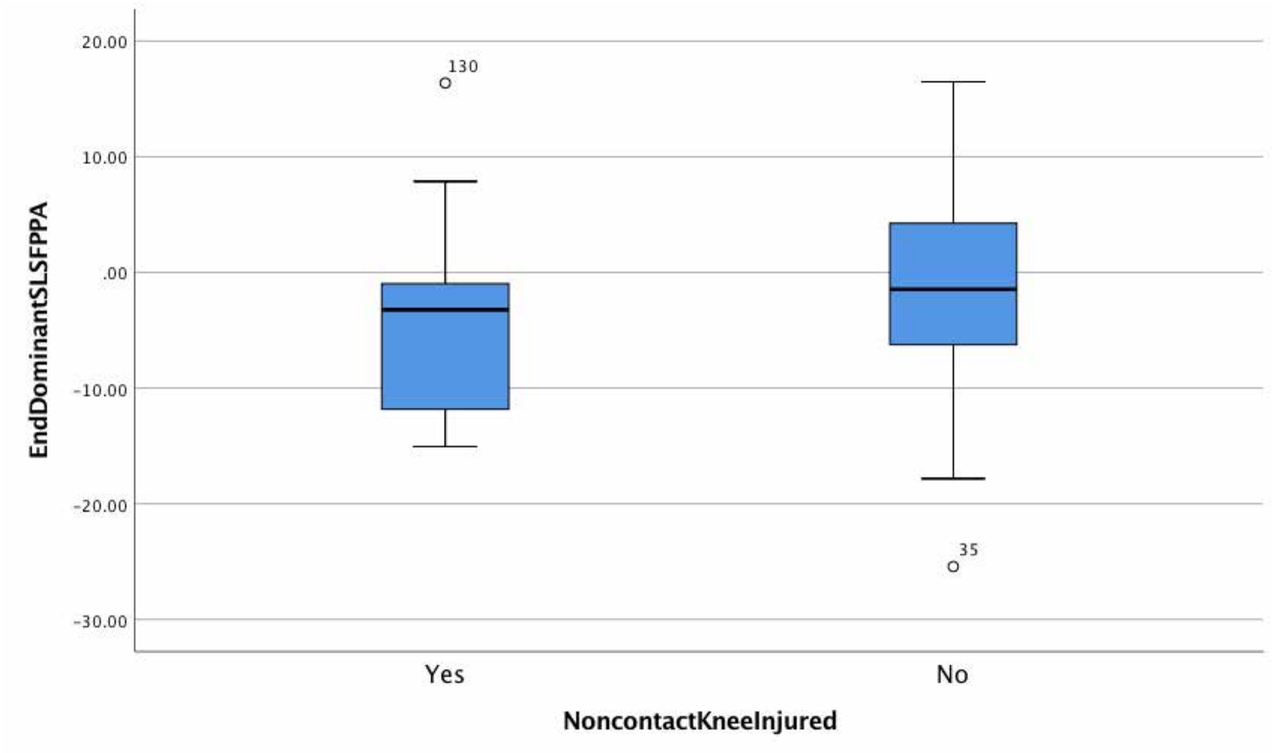
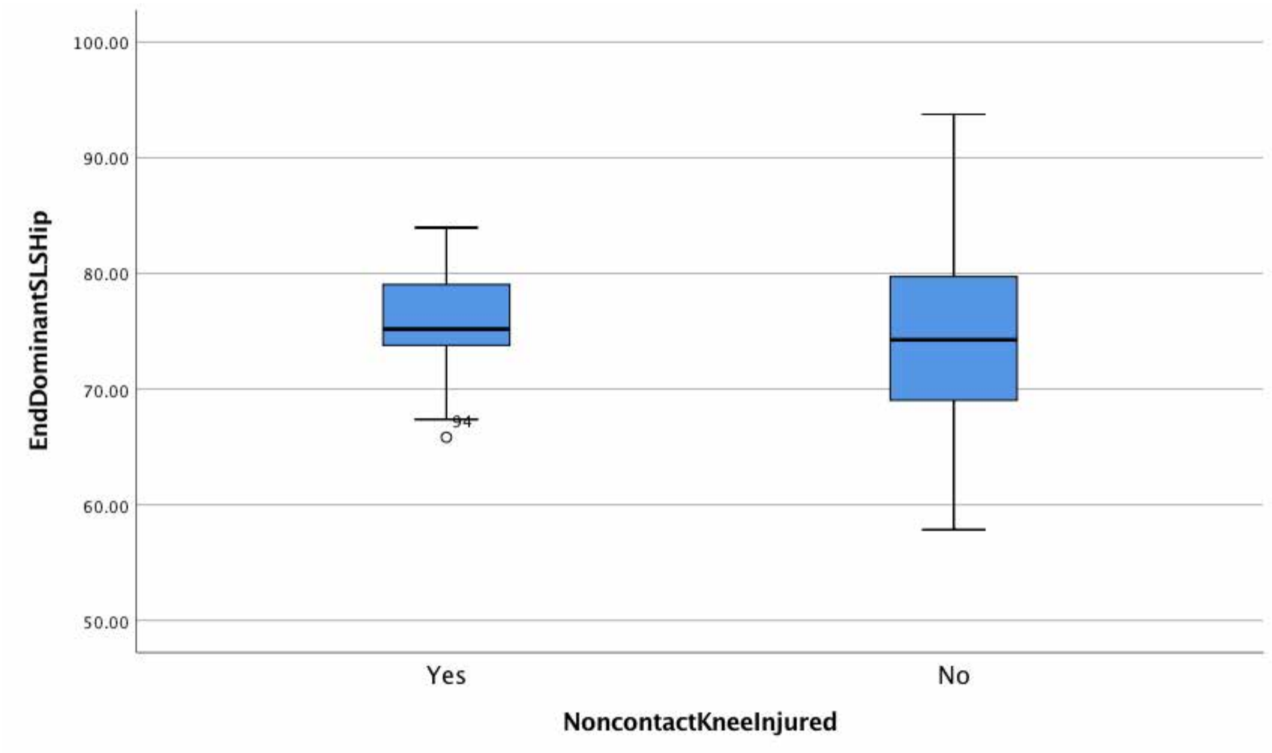


EndDominantSLSHip



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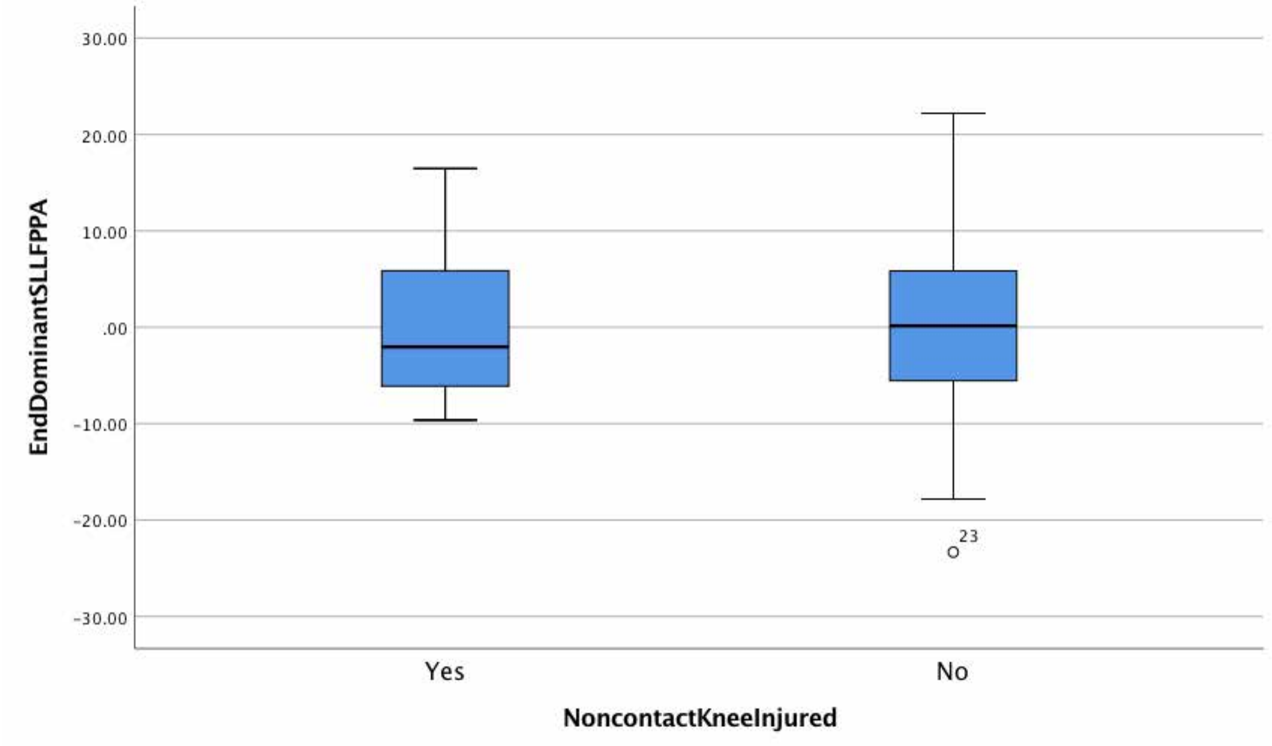
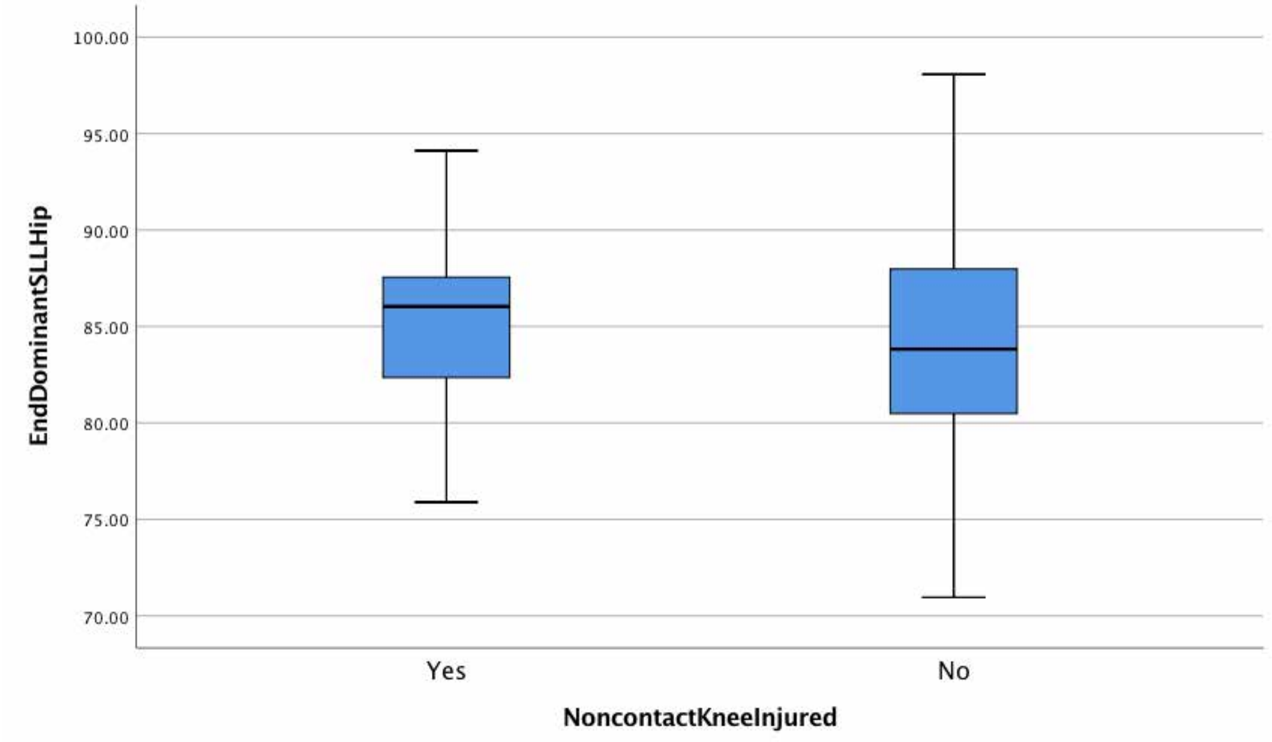


EndDominantSLLHip



Tests of Normality for performance-variability

	NoncontactKneeInjured	Kolmogorov-Smirnov[a] Statistic	df	Sig.	Shapiro-Wilk Statistic	df	Sig.
PreDominantSLSFPPASOCV	Yes	.091	17	.200*	.942	17	.342
	No	.081	103	.095	.947	103	.000
PreDominantSLSHipSOCV	Yes	.218	17	.030	.886	17	.039
	No	.094	103	.027	.966	103	.009
PreDominantSLLFPPASOCV	Yes	.191	17	.099	.868	17	.020
	No	.136	103	.000	.929	103	.000
PreDominantSLLHipSOCV	Yes	.141	17	.200*	.899	17	.066
	No	.074	103	.188	.976	103	.058
StartDominantSLSFPPASOCV	Yes	.109	17	.200*	.957	17	.576
	No	.106	103	.007	.936	103	.000
StartDominantSLSHipSOCV	Yes	.120	17	.200*	.956	17	.559
	No	.095	103	.024	.941	103	.000
StartDominantSLLFPPASOCV	Yes	.141	17	.200*	.932	17	.236
	No	.120	103	.001	.914	103	.000
StartDominantSLLHipSOCV	Yes	.161	17	.200*	.944	17	.371
	No	.064	103	.200*	.955	103	.001
EndDominantSLSFPPASOCV	Yes	.195	17	.085	.831	17	.006
	No	.128	103	.000	.923	103	.000
EndDominantSLSHipSOCV	Yes	.088	17	.200*	.981	17	.962
	No	.131	103	.000	.941	103	.000
EndDominantSLLFPPASOCV	Yes	.108	17	.200*	.955	17	.538
	No	.098	103	.017	.935	103	.000
EndDominantSLLHipSOCV	Yes	.203	17	.062	.868	17	.020
	No	.106	103	.006	.924	103	.000

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The reliability and criterion validity of 2D video assessment of single leg squat and hop landing

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ABSTRACT

The objective was to assess the intra-tester, within and between day reliability of measurement of hip adduction (HADD) and frontal plane projection angles (FPPA) during single leg squat (SLS) and single leg landing (SLL) using 2D video and the validity of these measurements against those found during 3D motion capture. 15 healthy subjects had their SLS and SLL assessed using 3D motion capture and video analysis. Inter-tester reliability for both SLS and SLL when measuring FPPA and HADD show excellent correlations ($ICC_{2,1}$ 0.97–0.99). Within and between day assessment of SLS and SLL showed good to excellent correlations for both variables ($ICC_{3,1}$ 0.72–91). 2D FPPA measures were found to have good correlation with knee abduction angle in 3-D ($r = 0.79$, $p = 0.008$) during SLS, and also to knee abduction moment ($r = 0.65$, $p = 0.009$). 2D HADD showed very good correlation with 3D HADD during SLS ($r = 0.81$, $p = 0.001$), and a good correlation during SLL ($r = 0.62$, $p = 0.013$). All other associations were weak ($r < 0.4$). This study suggests that 2D video kinematics have a reasonable association to what is being measured with 3D motion capture.

1. Introduction

Three dimensional (3D) motion analysis has been used extensively to assess kinematic and kinetic variables during lower limb motion. It has been regarded as the 'gold standard' for the assessment of potentially high risk manoeuvres related to a variety of knee injuries (McLean et al., 2005). Although 3D motion capture is considered the gold standard for kinematic and kinetic analysis, it is frequently not used in the clinical environment or for pre-participation screening, possibly due to the time required to acquire and analyse the data, large cost of equipment, and the training needed to effectively use it. In the place of 3D motion capture, 2-dimensional (2D) video motion analysis has been used to quantify hip and knee kinematics (Munro et al., 2012). 2D motion capture though has an inherent limitation as it cannot measure kinematics that occurs in planes not perpendicular to the camera without potential for perspective error. As such, 2D motion capture may not be suitable for performance assessment of any motion that is not purely uniplanar such as the knee valgus motion at the knee, which in reality is a movement not only comprising of knee abduction and hip adduction in the frontal plane but also hip internal rotation and tibial external rotation in the coronal plane (Malfait et al., 2014). The work of McLean et al. (2005) confirmed this noting that 2D knee valgus angles were inherently influenced by hip and knee joint rotations.

The extent to which non-uniplanar motions can be reflected in the uniplanar knee motion, measured with 2D video, has only been investigated in a limited number of studies. These studies have tested for a relationship between 2D measures of knee and hip motion and 3D hip and knee kinematics. For example, McLean et al. (2005) reported the relationship between 2D and 3D motion capture in assessing frontal-plane knee kinematics during side-stepping, side-jumping, and shuttle run. They reported strong correlations of $r = 0.76$ and 0.80 between peak knee abduction angles during 2D and 3D motion capture for side-stepping and side-jumping, respectively; however, the shuttle run yielded a much lower relationship of just $r = 0.20$. Sorenson et al. (2015) found a strong relationship between 2D frontal plane projection angle (knee abduction angle) and 3D knee abduction angle ($R^2 = 0.72$), and between 2D hip adduction and 3D hip adduction ($R^2 = 0.52$) during single leg hop landings. Gwynne and Curran (2014) found FPPA to correlate strongly with 3D knee abduction angle during single leg squat ($r = 0.78$). The study of Willson and Davis (2008)

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found 2D knee abduction angle reflected 23–30% of the variance of 3-D kinematic measurements during single leg squat, and also found knee abduction angle to be significantly correlated with hip adduction ($r = 0.32$). However, none of these studies have looked at the relationship of 2D frontal plane measures to movements in other planes, or the external moments generated at the hip and knee.

There are currently only a limited number of publications which have reported reliability of 2D FPPA for both single leg squat and single leg landing (Gwynne and Curran, 2014; Munro et al., 2012). There would appear to be no studies which have reported on reliability of the 2D video measurement of hip adduction angle during these tasks.

The overall aim of the study was to assess the reliability and validity of 2D kinematic video analysis of single leg squat and single leg landing, specifically: to assess the intra-tester and within and between day reliability of measurement of hip adduction and frontal plane projection angles during SLS and SLL using 2D video; and to assess the validity of these measurements against those found during 3D motion capture. The three hypotheses which will be tested by this study are: that 2D video parameters will have validity when compared to equivalent 3D parameters; 2D parameters measured will show strong between individual and within and between session reliability.

2. Method

2.1. Participants

Fifteen physically active healthy participants, after giving informed consent, volunteered to participate in this study which was approved by the university research ethics committee. Participants had to be free from lower limb or spinal injury or history of injury to participate in the study. Participant's details are to be found in Table 1.

2.2. Procedures

2.2.1. Single leg squat (SLS)

Participants were asked to stand on the test limb, facing the video camera. They were asked to squat down as far as possible, to at least 45° knee flexion, over a period of 5 s. Knee-flexion angle was checked during practice trials using a standard goniometer (Gaiam-Pro), and then observed by the same examiner throughout the trials. There was also a counter for each participant over this 5-s period, in which the first count initiates the movement, the third indicates the lowest point of the squat and the fifth indicates the end. This standardises the test for the participant, thereby reducing the effect of velocity on knee angles. Trials were only accepted if the participant squatted to the minimum desired degree of knee flexion and maintained balance throughout.

2.2.2. Single-leg landing (SLL)

Participants dropped from a 28-cm step, leaning forward and dropping as vertically as possible. They were asked to take a unilateral stance on the ipsilateral limb and to hop forward to drop onto the force platform, ensuring that the contralateral leg made no contact with the ground on landing.

Table 1
Participant demographics.

Characteristic	Gender	
	Males (N = 8)	Females (N = 7)
Age (years)	25.0 (±6.4)	26.6 (±3.5)
Height (cm)	171.0 (±6.7)	163.0 (±5.4)
Mass (kg)	69.7 (±10.7)	63.0 (±8.0)

2.2.3. 3D motion capture

The method is based on the procedure previously reported in Alenezi et al. (2014). A ten-camera motion analysis system (Pro-Reflex, Qualisys, Sweden), sampling at 240 Hz, and a force platform embedded into the floor (AMTI, USA), sampling at 1200 Hz, were used to collect kinematic and kinetic variables during the support phase of single leg squat and landing tasks. Before testing, participants were fitted with the standard training shoes (New Balance, UK) to control shoe-surface interface. Reflective markers (14 mm) were attached with self-adhesive tape to the participants' lower extremities over the following landmarks; anterior superior iliac spines, posterior superior iliac spines, iliac crest, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, posterior calcanei, and the head of the first, second and fifth metatarsals (Fig. 1). The tracking markers were mounted on technical clusters on the thigh and shank with elastic bands. The foot markers were placed on the shoes, and the same individual placed the markers for all participants. The calibration anatomical systems technique (CAST) was employed to determine the six-degree of freedom movement of each segment and anatomical significance during the movement trials. The static trial position was designated as the participants' neutral (anatomical zero) alignment, and subsequent kinematic measures were related back to this position. The markers were removed and replaced for the within-session trials and removed and replaced for the between-day trials. To orientate participants with the tasks, each participant was asked to perform 3–5 practice trials of each task before data collection. Participants were required to complete five successful trials for each task. Visual 3D motion (Version 4.21, C-Motion Inc., USA) was used to calculate the joint kinematic and kinetic data. Motion and force plate data were filtered using a Butterworth 4th order bi-directional low-pass filter with cut-off frequencies of 12 Hz and 25 Hz, respectively, with the cut-off frequencies based

Fig. 1. Marker position and lines used for calculation of FPPA.

on a residual analysis (Yu et al., 1999). All lower extremity segments were modelled as conical frustra, with inertial parameters estimated from anthropometric data (Dempster, 1959). Joint kinematic data was calculated using an X–Y–Z Euler rotation sequence. Joint kinetic data were calculated using three-dimensional inverse dynamics, and the joint moment data were normalised to body mass and presented as external moments referenced to the proximal segment. External moments were described in this study, for example, an external knee valgus load will lead to abduct the knee (valgus position), and an external knee flexion load will tend to flex the knee. The following discrete variables were calculated for each trial: peaks of hip internal rotation and adduction moments, knee abduction moment, and peaks of lower limb joint angles at frontal, sagittal, & transverse planes for the hip and knee.

2.2.4. 2D video assessment

Before testing, markers were placed on the lower extremity of each participant to approximate the radiographic landmarks employed by Willson et al. (2006) and Willson and Davis (2008). Markers were placed at the midpoint of the femoral condyles to approximate the centre of the knee joint, midpoint of the ankle malleoli for the centre of the ankle joint, and on the proximal thigh along a line from the anterior superior iliac spine to the knee marker, markers were also placed on the anterior superior iliac spines. The midpoints were determined using a standard tape measure, and all markers were placed by the same experimenter. These markers were used in order for FPPA of the knee and hip adduction angles to be determined from digital images using Quintic software package (9.03 version 17). Digital video footage was captured at the same time as 3D, recorded at a standard 10× optical zoom using a Sony HandycamDCR-HC37 camera positioned at a height of 60 cm, 10 m away from the participants and directly in front, after which the footage was downloaded to Quintic. A single experimenter digitised the markers placed on the participant across the three sessions, with another experimenter digitising the video from the first sessions to provide data for the inter-tester reliability element.

2.3. Outcome measures from 2D video

The frontal plane projection angle and the hip adduction angle were collected from the videos of all participants for all tasks. Frontal plane projection angle (FPPA) of the knee was measured as the angle subtended between the line from the markers on the proximal thigh to the knee joint and the line from the knee joint to the ankle at the frame that corresponded with the point of maximum knee flexion. Positive FPPA values reflected knee valgus, excursion of the knee toward the midline of the body so that the knee marker was medial to the line between the ankle and thigh markers, and negative FPPA values reflected knee varus. The hip adduction angle (HADD) was measured as an angle subtended between the line from the markers on the proximal thigh and the line between the two anterior superior iliac spines. In Fig. 1 the lines used are superimposed in the figure.

Participants were tested twice on day 1 (tests 1 and 2), with the tests separated by 1 h, to assess within day reliability. Participants were then tested again exactly 1 week later (test 3) at the same time of day to assess between-days reliability. Participants were allowed practice trials before each test until they felt comfortable; this was typically 2 or 3 trials. After familiarisation each participant performed 3 trials of each test. Both legs were tested and analysed for all tests.

2.4. Analysis

Inter-tester reliability was assessed by two of the authors independently viewing the 2D videos of the first assessment session, and measuring FPPA and hip adduction angles from SLS and SLL for all participants, then the findings were compared using intra-class correlation (model 2,1). Within and between session reliability was assessed when a single examiner viewed the 2D videos of the first, second and third assessment sessions, and measuring FPPA and hip add angles from SLS and SLL for all participants, then comparing findings for within day and between day reliability using intra-class correlation (model 3,1). The standard error of measurement was also calculated for all variables using the formula SEM = SD (pooled) × ($\sqrt{1-\text{ICC}}$) (Thomas et al., 2005). The criterion validity of the 2D measures was then assessed by comparing the findings from the first assessment of SLS and SLL to the findings from 3D motion capture undertaken at the same time using a Pearson's product moment correlation. Paired T-tests were ran to ensure that there is no consistent between- or within-day difference in the means between rater one and rater two, between sessions and between 2D and 3D values.

3. Results

3.1. Inter-tester 2D video measurement reliability

Inter-tester reliability between two testers of the video capture technique has been assessed in both tasks the ICC's and standard error of measurement (SEM) are shown in Table 2. In SLS, the correlation was found to be very large for both variables. FPPA and HADD reported correlations were ($r = 0.97$, $p = 0.001$), ($r = 0.96$, $p = 0.001$) respectively. Also, FPPA and HADD were found to be highly correlated ($r = 0.99$, $p = 0.001$), ($r = 0.99$, $p = 0.001$) respectively in SLL.

3.2. Within and between day 2D video measurement reliability

Table 3 shows the within and between session ICC's and SEM's. In SLS, 2D FPPA measures demonstrated good within-session (ICC = 0.72, 95% CI = 0.09–0.92) reliability. The 2D HADD also demonstrated good within-session (ICC = 0.91, 95% CI = 0.71–0.97) reliability. The SLL, within-session reliabilities were (ICC = 0.87, 95% CI = 0.58–0.96), (ICC = 0.89, 95% CI = 0.65–0.97) for FPPA and HADD respectively. The SLS, 2D FPPA measures showed good between-session (ICC = 0.87, 95% CI = 0.57–0.96) reliability, along with 2D HADD demonstrating good between session (ICC = 0.79, 95% CI = 0.32–0.94) reliability. While during SLL, between-session reliabilities were (ICC = 0.87, 95% CI = 0.58–0.96), (ICC = 0.86, 95% CI = 0.54–0.96) for FPPA and HADD respectively.

3.3. Correlation 2D measurements to 3D motion capture kinematic and kinetic values

Table 4 shows the correlations between 2D and 3D variables. 2D FPPA measures were found to have good correlation with knee abduction angle in 3-D ($r = 0.79$, $p = 0.008$) during SLS. Also, 2D FPPA was found to be correlated with knee abduction moment ($r = 0.65$, $p = 0.009$) during SLS. 2D HADD showed very good correlation with 3D HADD during SLS ($r = 0.81$, $p = 0.001$), and a good correlation during SLL ($r = 0.62$, $p = 0.013$). All other associations were weak ($r < 0.4$) and not significant ($p > 0.05$).

Table 5 shows the mean values for hip adduction and knee abduction (FPPA) across sessions for both raters and for 3D motion capture. Paired t-tests were ran on this data the results are shown

Table 2
Inter-tester reliability.

	Single leg Squat		Single leg Land	
	FPPA	Hip Add	FPPA	Hip Add
ICC (95% CI)	0.97 (0.91–0.99)	0.96 (0.89–0.99)	0.99 (0.97–1.0)	0.99 (0.97–1.0)
SEM (°)	1.97	1.96	1.99	1.99

Table 3
Within and between day reliability of 2D video.

	Single leg Squat				Single leg land			
	Within session		Between session		Within session		Between session	
	FPPA	Hip Add	FPPA	Hip Add	FPPA	Hip Add	FPPA	Hip Add
ICC (95% CI)	0.72 (0.09–0.92)	0.91 (0.71–0.97)	0.87 (0.57–0.96)	0.79 (0.32–0.94)	0.87 (0.58–0.96)	0.89 (0.65–0.97)	0.87 (0.58–0.96)	0.86 (0.54–0.96)
SEM (°)	1.72	1.37	1.93	1.93	1.43	1.32	1.4	1.43

Table 4
Correlation 2D measurements to 3D motion capture kinematic and kinetic values.

3D motion capture measurements	2D video measurements			
	Single leg Squat		Single leg Land	
	FPPA	Hip adduction angle	FPPA	Hip adduction angle
Hip adduction angle	r = 0.45 (p = 0.1)	**r = 0.81 (p = 0.001)**	r = 0.13 (p = 0.65)	**r = 0.62 (p = 0.013)**
Hip adduction moment	r = 0.27 (p = 0.34)	r = 0.29 (p = 0.41)	r = 0.22 (p = 0.44)	r = 0.1 (p = 0.9)
Hip internal rotation angle	r = 0.16 (p = 0.56)	r = 0.6 (p = 0.18)	r = 0.33 (p = 0.23)	r = 0.2 (p = 0.47)
Hip internal rotation moment	r = 0.41 (p = 0.32)	**r = 0.45 (p = 0.09)**	r = 0.37 (p = 0.16)	r = 0.1 (p = 0.78)
Knee Abduction angle	**r = 0.79 (p = 0.008)**	r = 0.25 (p = 0.37)	r = 0.21 (p = 0.79)	r = 0.36 (p = 0.19)
Knee abduction moment	**r = 0.65 (p = 0.015)**	r = 0.12 (p = 0.68)	r = 0.36 (p = 0.19)	r = 0.01 (p = 0.9)

Table 5
Mean (standard deviation) measurements for hip adduction and knee abduction angles (FPPA) across sessions and for second tester (2D video) and for 3D motion capture.

Task	Single leg Squat					Single leg landing				
Session	1	1 (Rater 2)	1 (3D)	2	3	1	1 (Rater 2)	1 (3D)	2	3
FPPA (Hip abduction)	−9.1 (10.6)	−11.3 (11.3)[a]	−7.8 (4.7)[b]	−10.2 (7.8)[c]	−11.7 (9.8)[d]	−10.9 (6.4)	−11.2 (6.4)[a]	−8.4 (5.0)[b]	−10.3 (6.5)[c]	−10.9 (5.8)
Hip Adduction	70.6 (8.7)	70.6 (8.3)[a]	74.9 (6.3)[b]	71.7 (7.5)[c]	70.5 (8.2)[d]	79.1 (5.2)	78.8 (5.6)[a]	81.9 (5.7)[b]	80.2 (6.5)[c]	81.2 (6.6)[d]

[a] No significant difference between rater one and rater two ($p > 0.05$).
[b] No significant difference between rater one and 3D motion capture ($p > 0.05$).
[c] No significant difference between session 1 and session 2 ($p > 0.05$).
[d] No significant difference between session 1 and session 3 ($p > 0.05$).

in table 5 and show no significant differences between values across all comparisons.

4. Discussion

In line with previous work (Gwynne and Curran, 2014; Munro et al., 2012) 2D assessment was shown to be reliable within and between days. In Munro et al. (2012) SLS within day reliability was 0.59–0.86 and in Gwynne and Curran (2014) it was 0.86 (our study 0.72) and between day 0.72–0.82 (Munro et al., 2012), 0.74 (Gwynne and Curran, 2014) our study 0.87. In Munro et al. (2012) for SLL within day 0.75–0.79 versus 0.87 and between days 0.8–0.82 versus 0.87. Generally the standard error of measurement (SEM) in our study was slight less than those reported in Munro et al. (2012) and Gwynne and Curran (2014) across the tasks. It is not clear why our study found between session reliability to be slightly better in terms of the ICC values than within day for SLS (Table 3), it might be partially explained by the larger confidence intervals for within day, though there was no significant difference in mean scores (Table 5). No previous work has attempted to assess inter-tester reliability for the assessment of FPPA or hip adduction angles from the videos during SLS or SLL so our findings cannot be compared to previous work. It would appear from our data that the method undertaken to assess FPPA and HADD for all tasks shows excellent inter-tester reliability. The findings of this paper along with those of Gwynne and Curran (2014) and Munro et al. (2012) would indicate that the methods used are robust enough to provide reliable results across multiple testers and time points, this opens up the possibility of using these tests in multi-centre trials.

There are only a limited number of studies which have investigated the association between 2D and 3D knee and hip motion during functional tasks. These studies have generally, despite measuring the relationships during different tasks, found moderately strong correlations between certain parameters when undertaking 2D and 3D motion capture in line with the findings of this study (McLean et al., 2005). When assessing similar tasks, in for instance the study of Sorenson et al. (2015) they found FPPA had a strong relationship to 3D knee abduction angle ($r^2 = 0.72$) during SLL, similar to the current studies findings. Willson and Davis (2008) found a moderate relationship during SLS of FPPA to knee abduction angle assessed with 3D ($r = 0.48$), though only a weak one with HADD ($r = 0.37$), which differs slightly from our study. Gwynne and Curran (2014) found a strong relationship between FPPA during SLS and 3D knee abduction angle (r = 0.78). Ageberg et al. (2010) reported 3D hip internal rotation rather than knee abduction angle appeared to be related to a knee medial to the foot position during a single leg squatting task, this study could be regarded as showing partial agreement with their findings as there was a poor correlation between hip internal rotation angle and FPPA.

When the findings from the literature along with ours are taken on the whole, it would appear that both FPPA and HADD measured using 2D video bear a moderate to good relationship with the comparable measures produced with 3D motion capture, especially for less complex and dynamic tasks such as SLS. The difference in validity between the two tasks (SLS and SLL) might be due to the difference between the tasks and their impact on matching the exact moment of maximum knee flexion angle. FPPA was captured at the point of maximum flexion, because of the different capture speeds of the two systems being compared, during is the high speed task of SLL, the poor correlation could relate to an inability to be measuring at exactly the same knee flexion point. Whereas during the slower task of SLS it is more likely the two systems coalesce.

This study has limited generalisability as the relationships were only found in uninjured individuals and further study is required to identify if these or different relationships occur in individuals with pathology. In addition, as with other 3D motion capture studies using external marker sets, skin-movement artefact has the potential to influence such data. The intrinsic difference in sampling frequency between the two measurement systems used may influence the relationships found as there may have been temporal differences in the data extracted from each system leading to systematic error. Similarly different markers were used for measurement for the two systems which again could have led to some systematic error. Future research should perhaps consider using the same markers and taking care to measure at the same points. Further research is needed to identify whether the current findings extend to analyses performed using clinical techniques, as well as during other activities such as bilateral leg landings, cutting activities, and other dynamic tasks. Inter-tester reliability in this study only assessed the agreement between the two assessors in extracting the relevant angles from the 2D videos. The potential sources of inter-tester error could be: (1) placement of the markers; (2) digitization of the markers; (3) measure of the angles; the inter-tester reliability in this study only tested the latter two sources, it did not assess the first source.

This study adds to the growing body of evidence suggesting 2D video analysis of a variety of single leg tasks, have a reasonable association to what is being measured using 3D motion capture. The findings of this study also show the approach has good reliability, within and between sessions and also between examiners.

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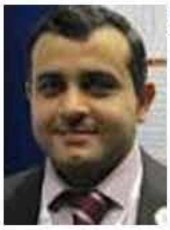

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